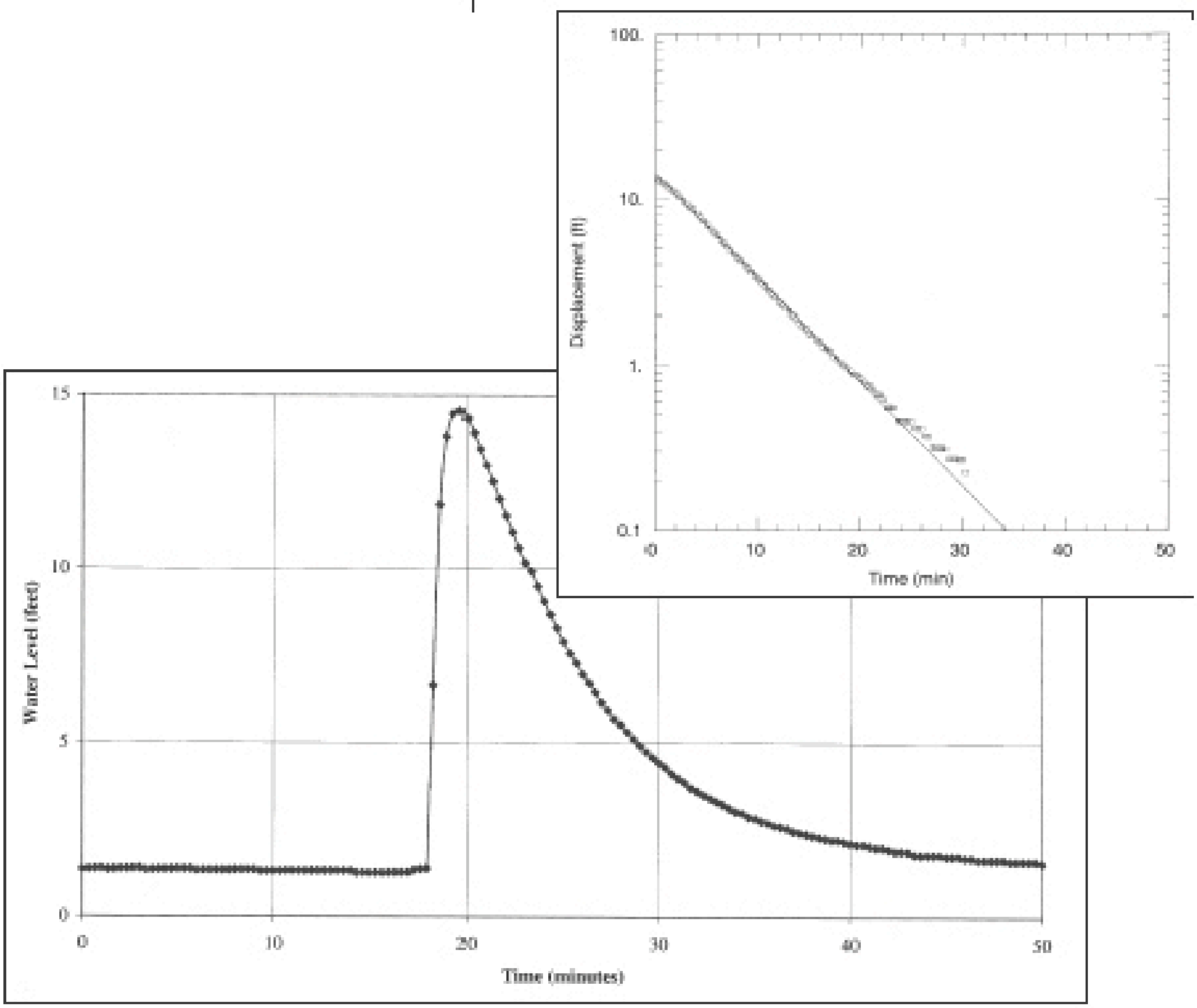
LA-13987-MS

Hydrologic Tests at Characterization Wells R-9i, R-13, R-19, R-22, and R-31



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The cover shows typical field (left) and analytical (right) plots for the straddle-packer/injection tests reported in this document. Values for hydraulic properties of saturated materials beneath the Pajarito Plateau are needed for various environmental efforts at Los Alamos National Laboratory. Hydrologic testing of the deep wells being installed under the Hydrogeologic Workplan is producing such data.

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Los Alamos
NATIONAL LABORATORY

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ABBREVIATIONS, ACRONYMS, AND NOTATION

ASTM	American Society for Testing and Materials
bgs	below ground surface
EES	Earth and Environmental Sciences (Division)
EPA	Environmental Protection Agency
ER	Environmental Restoration (Project)
ft/d	feet per day (hydraulic conductivity unit)
ft^2/d	feet squared per day (transmissivity unit)
FY	fiscal year
gpd/ft^2	gallons per day per square foot (hydraulic conductivity unit)
gpm	gallons per min (discharge unit)
hp	horse power
I.D.	inside diameter
IM	Information Management (Division)
K	hydraulic conductivity
LANL	Los Alamos National Laboratory
MDA	Material Disposal Area
O.D.	outside diameter
NMED	New Mexico Environment Department
NTU	nephelometric turbidity units
RRES	Risk Reduction and Environmental Stewardship (Division)
s	water-level change relative to static position (drawdown)
S	storativity
SAIC	Science Applications International Corporation
SOP	standard operating procedure
t	time since testing began
T	transmissivity
TA	Technical Area
TD	total depth
TOC	total organic carbon
UDR	underground drill rig
y	displacement of water level in slug testing

HYDROLOGIC TESTS AT CHARACTERIZATION WELLS R-9i, R-13, R-19, R-22, AND R-31

by
William J. Stone and Stephen G. McLin

ABSTRACT

Hydrologic information is essential for environmental efforts at Los Alamos National Laboratory. Testing at new characterization wells being drilled to the regional aquifer ("R wells") to improve the conceptual hydrogeologic model of the Pajarito Plateau is providing such information. Drilling has been by air-rotary casing-advance or open-hole methods. Most wells are completed with multiple screens. After their construction, wells were rigorously developed by wire-brushing, bailing, followed by surging, swabbing, or jetting, and finally by pumping. These methods are effective based on field-parameter measurements and comparison of results of hydrologic testing at well R-31 before and after complete well development.

We conducted field tests on various zones of saturation penetrated by the R wells to collect data needed for determining hydraulic properties. This document provides details of the design and execution of testing as well as an analysis of data for five of the new wells: R-9i, R-13, R-19, R-22, and R-31. One well was evaluated by a pumping test (R-13), another was evaluated by both straddle-packer/injection and pumping tests (R-9i), and the rest were evaluated by injection tests alone (R-19, R-22, R-31).

Testing was constrained by the regional setting (complex geology and multiple zones of saturation) and well construction (multiscreen completion and the small diameter of the production casing). Packers are required for testing multiscreen wells. The small diameter of the production casing not only precludes the use of a slugger but also limits the capacity of pumps that can be used in testing, especially for the depths involved in the R wells. For example, pumping at a maximum rate of 19 gallons per minute did not significantly stress the regional aquifer at R-13.

Although not slug tests, the injection tests are comparable in several ways, and analysis of data by slug-test methods is appropriate. Despite constraints, the results obtained appear valid based on (1) the care taken during test implementation and data analysis, (2) comparison of results for initial and repeated tests obtained by the same analytical method, (3) comparison of results obtained for a given test by different analytical methods, (4) comparison of results with values determined by geophysical logging in the wells and pumping tests of the same geologic units elsewhere on the plateau, and (5) comparison with hydraulic properties commonly reported for similar geologic materials outside the area.

Significant contributions of this report are not only the documentation of test design, implementation, and analysis but also a comprehensive table showing the distribution of hydraulic properties for the saturated geologic units tested beneath the Pajarito Plateau.

We also offer several recommendations based on testing to date. Placing screens across the water table and geologic contacts as well as employing oversized filter packs hinders testing and should be avoided. In addition, we recommend that future testing include some alternative designs and methods. Multiple methods and routine repeat testing for a given screened interval would permit comparison of results.

INTRODUCTION

Hydrologic information is essential for surveillance efforts, environmental restoration activities as well as numerical modeling of groundwater flow and transport at Los Alamos National Laboratory (LANL or the Laboratory). Various kinds of hydrologic observations at new wells being drilled across the Pajarito Plateau under the Hydrogeologic Workplan (LANL 1998, 59599) provide this information. Saturated zones are identified and characterized as to water level, stratigraphic unit, hydraulic condition (unconfined or confined), and scale (perched or regional). Head measurements at different depths within the regional zone of saturation indicate the direction of the vertical gradient. Field hydrologic tests provide data for determining hydraulic properties of the saturated media. As the new wells penetrate the regional water table and are completed in the regional aquifer, they are identified by an "R" prefix and are commonly referred to as "R wells."

This document reports on the collection to date of hydraulic-property data from the new deep R wells. The well-completion reports present only brief summaries and preliminary results of hydrologic testing. By contrast, this document captures and preserves details of the design, execution, and analysis of such tests as well as a discussion of the quality of the data and results obtained. More specifically, this report describes tests performed at five wells (Figure 1). This includes one intermediate-depth offset well (R-9i) and four deep characterization wells (R-13, R-19, R-22, and R-31).

Testing at seven other R wells recently installed on the plateau is not discussed in this report for the following reasons. Low water production or placement of screens across the water table precluded meaningful testing of saturated hydraulic properties at wells R-5 and R-7. Data from testing at well R-8A were lost before they could be analyzed because of equipment malfunction. Tests conducted by contractors at wells R-9 and R-12 are invalid because of variable flow rates during the tests. A report on the pumping test at well R-15 is being prepared separately. Testing at well R-25 was inconclusive because introduced water was rejected and there were no falling-head data to analyze.

Information presented below for the hydrogeology and construction of all but one of the wells comes from completion reports. Final reports are available for wells R-9i (Broxton et al. 2001, 66600), R-19 (Broxton et al. 2001, 71253), R-22 (Ball et al. 2001, 71471), and R-31 (Vaniman et al. 2001, 72615). As the report for R-13 is not yet written, information presented for R-13 comes from the Fact Sheet prepared for the well. The stratigraphy shown for most of the wells differs slightly from that in the completion reports as a result of additional analysis since the reports were published. It should be noted at the outset that the term Cerros del Rio basalt is an informal name commonly applied to local Tertiary lavas of various compositions (not all basaltic).

Some conventions were adopted to enhance the clarity, usefulness, and consistency of this report. Reference citations for the analytical methods used are only given under Data Analysis to avoid repetition in the text. Tables summarizing tests in the text are placed in boxes for quick identification and reference. Labels given within the analytical plots serve the same purpose; these are based on the well and screen number, for example R-9i-1. Various letters at the end of such labels identify specific conditions: a = the first test when there was a repeat test, b = the repeat test, P = pumping-test data, D = drawdown data, E = early-time drawdown data, L = late-time drawdown data, and R = recovery data. Although the design and results of repeat tests are given in the summary tables, analytical plots are not presented in the interest of saving space. Graphs and raw field data for water level versus time as well as additional analytical data for the selected tests are given in the appendices.

OVERVIEW OF WELLS

Deep wells to the regional zone of saturation are being installed at the Laboratory as part of a program to improve the conceptual hydrogeologic model for the Pajarito Plateau (LANL 1998, 59599). Although some of these wells may become part of the groundwater surveillance network, they are characterization wells. That is, each provides geologic, hydrologic, and hydrochemical observations in an area where there are data gaps. The information obtained will be used to design a sound groundwater-monitoring network.

The drilling, construction, and development of the wells are briefly outlined below. Complete details can be found in the well-completion reports listed above. Methods used in drilling, constructing and developing the wells are compatible with Environmental Protection Agency (EPA) guidelines (Aller et al. 1991, 70112).

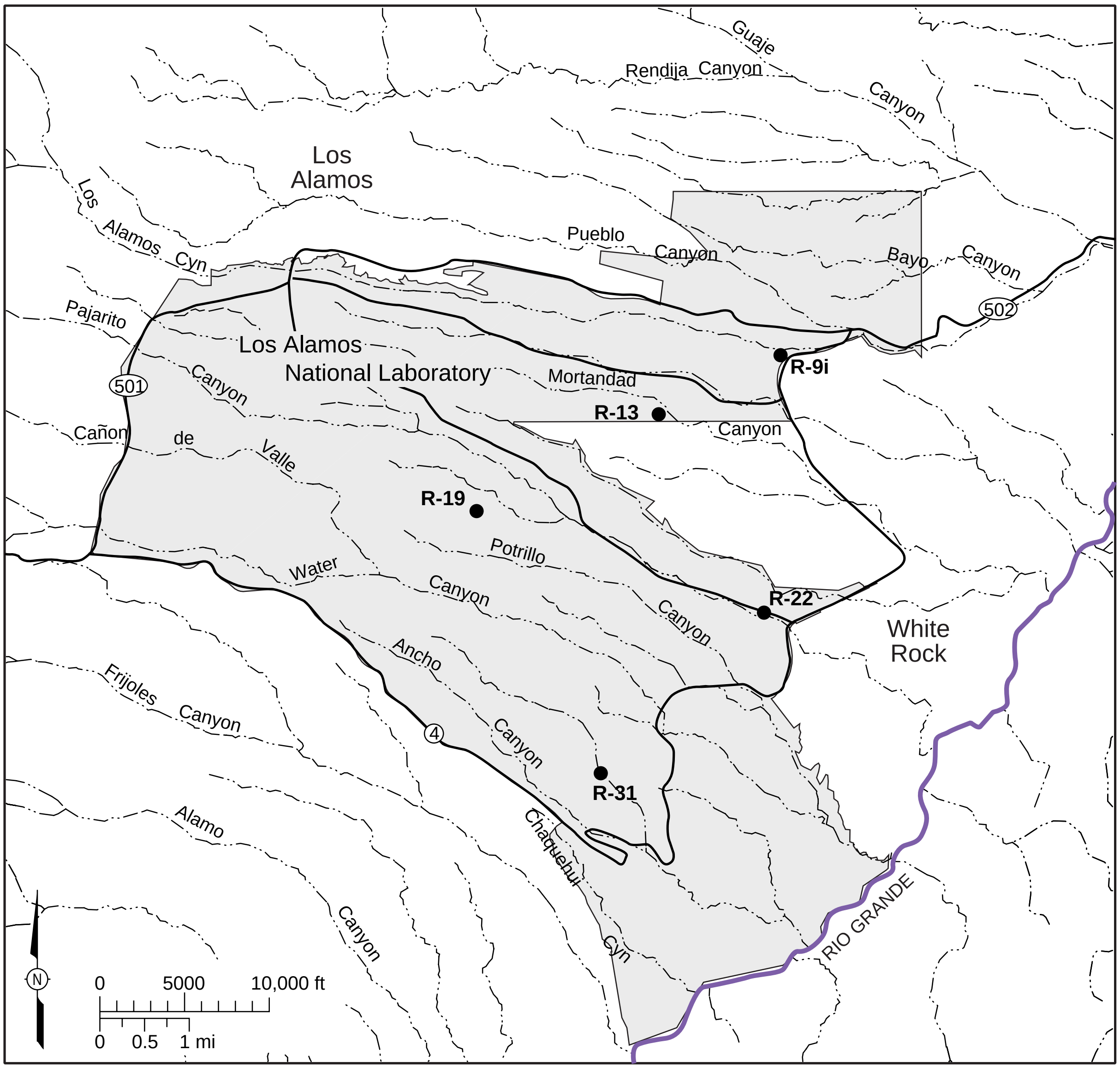

Figure 1. Location of wells tested

Drilling Methods

Drilling methods have changed throughout the deep-well program (Table 1). Initially, wells were drilled by air-rotary casing-advance and coring methods. More recently, drilling has been by open-hole methods, and geophysical logging has replaced coring as the means of supplementing both geologic and hydrologic observations. The holes have been drilled essentially dry so that saturated zones can be more easily recognized. However, water and minor amounts of various drilling fluids have been added at times to enhance lubricity during casing-advance operations or formation stability during open-hole operations.

Table 1
Drilling and Completion of Wells Tested

Well	Drilling Method	Circulation Fluid[a]	No. of Screens	Screen Type[b]	Open Area (%)[c]
R-9i	Air-rotary, open-hole	Air	2	Rod-based, wire-wrapped	7.9
R-13	Air-rotary, open-hole/ casing advance	Air and water (EZ-MUD plus QUIK FOAM)	1	Pipe-based, wire-wrapped	8.75
R-19	Air-rotary, casing-advance	Air and water (EZ-MUD plus QUIK FOAM, Torkease)	7	Pipe-based, wire-wrapped	8.75
R-22	Air-rotary, open-hole/ casing advance	Air and water (EZ-MUD plus QUIK FOAM)	5	Pipe-based, wire-wrapped	8.75
R-31	Air-rotary, open-hole/ casing advance	Air and water (Torkease, EZ-Mud plus)	5	Rod-based, wire-wrapped	7.9

[a] Air and water were the primary fluids; others listed were added only as deemed necessary.
[b] Wire-wrap in all screens is 10-slot stainless steel.
[c] For pipe-based screen, value given is that for drilled pipe.

Well Construction

Construction has varied slightly from well to well. As-built diagrams, provided for each well in the sections that follow, give specific details. Nonetheless, some generalizations are offered here as background.

Most of the wells are completed with multiple screens placed within perched and regional zones of saturation (Table 2). All screens are constructed of stainless steel and have a 0.010 in. slot size. Rod-based, wire-wrapped screens were used in wells R-9i and R-31. That is the more common type of wire-wrapped screen. These screens were fabricated with 32 rods and have an open area of 7.9%. Pipe-based, wire-wrapped screens were used in the other three wells. In that type of screen, a wire-wrapped jacket is placed around a pipe in which round holes have been drilled. In the screens used, the holes are 0.5 in. in diameter, and their density is up to 84 holes/ft. Open area for the drilled pipe is 8.75%. The New Mexico Environment Department (NMED) has required that the uppermost screens be positioned so that the upper 5 ft lie above the water table. Most screens are 10 ft long, except those straddling the regional water table, which are longer in anticipation of the water level declining with time.

Annular fill consists of primary and secondary filter packs as well as seals. Screened intervals are isolated from each other by seals in the annulus between filter packs. Annular-seal material generally consists of bentonite, but in some places additional cement seals were emplaced. Filter-pack material consists of sand in all wells described in this report. The primary filter pack is coarser (usually 20/40 sand) to ensure that water flows easily to the screen. The secondary filter pack is finer (usually 30/70 sand). It is placed between the primary filter pack and the seal to prevent bentonite from reaching the screen. These different sizes of sand are not distinguished on the construction diagrams for the wells tested. Rather, the total length of filterpack (sand) is illustrated.

Table 2
Hydrogeology and Construction of Wells Tested

Well	TD (ft)	Ground Elevation (ft)	Saturated Zone/Unit[a]	Saturated Interval (ft)[b]	Screen Number	Screened Interval (ft)[c]	Head (ft)[d]
R-9i	322	6383	UP/Tb	142–236	1	189–199	6241
			LP/Tb	264–282	2	270–280	6119
R-13	1133	6660	R/Tpf	883–TD	1	958–1019	5827
R-19	1885	7066	UP/Qbof	834–840	1	827–844	6337
	Sloughed		LP/Tpf	894–912	2	893–910	6241
	From 1902		R/Tpf	1178–TD	3	1171–1215	5888
					4	1410–1417	NA[e]
					5	1583–1590	NA
					6	1727–1734	5932 **t**
					7	1832–1839	5903 **t**
R-22	1489	6650	R/Tb	895–TD	1	872–914	5730 **t**
					2	947–989	5725 **t**
					3	1272–1279	5682 **t**
					4	1389–1385	5670 **t**
					5	1447–1452	<5670 **t**
R-31	1103	6362	P/Tb	439–455	1	439–455	Dry
			R/Tb	522–TD	2	515–546	5853 **w**
					3	666–676	5852 **w**
					4	827–837	5854 **w**
					5	1007–1017	5851 **w**

[a] Zone: U = upper, M = middle, L = lower; P = perched, R = regional; Unit: Qbof = Otowi Member ashflow, Bandelier Tuff, Tb = Cerros del Rio basalt, Tpf = Puye Formation, fanglomerate, Tsfb = Santa Fe Group basalt.

[b] Based on observations during drilling or geophysical logs.

[c] Top and bottom of open interval, not screen joints.

[d] Composite for screened interval; **t** indicates value based on static water level for packed-off interval at time of testing, **w** indicates value from Westbay transducer; otherwise, value is based on water level determined during drilling.

[e] NA = not available.

Well Development

After the wells were constructed, they were developed to (1) remove fines and drilling fluid from both the formation and filter pack behind the screen; (2) create a stable zone of filtration between the screen and formation; and (3) re-establish effective hydraulic conductivity near the well. In most cases, development followed a multiphase protocol (Table 3). Preliminary development involved various combinations of wire-brushing, bailing, airlifting, surging, or jetting. Screens were first wire-brushed to remove particles that might have settled in the larger openings of the pipe-based screen. Next, the sump and screens were bailed to remove the more turbid water from the well and thus protect the pump. Where deemed beneficial, surging, swabbing, or jetting followed bailing. Final development was by pumping.

Table 3
Methods Used to Develop Wells Tested

Well[a]	Preliminary Development					Final Development	
	Wire-Brushing	Surging[b]	Swabbing[c]	Airlifting	Jetting[d]	Bailing	Pumping
R-9i (m)	X					X	X
R-13 (s)	X	X	X			X	X
R-19 (m)	X			X	X	X	X
R-22 (m)	X					X	X
R-31 (m)	X	X		X		X	X

[a] (m) = multi-screen completion; (s) = single-screen completion
[b] Done with surge block attached to wireline (not to rod)
[c] Involves flowing water out through screen from between two surge blocks
[d] Done with perforated pipe (not conventional jetting tool)

Development of pipe-based screen is difficult because there are two layers of openings. The effectiveness of well development was evaluated by means of several field parameters (pH, specific conductance, temperature, and turbidity). These were monitored at the outset of bailing and at regular intervals during pumping. When turbidity was <5 nephelometric turbidity units (NTU) or could not be improved, the pump was turned off, and the well was allowed to rest for a short interval. Then pumping was resumed briefly and field parameters were monitored at regular intervals to see if the previously obtained turbidity value could be reproduced. This process (pump off/on) was repeated three times. When the turbidity value could be reproduced, a sample was usually collected and analyzed for total organic carbon (TOC), a good indicator of the presence of drilling fluid. If the analytical result approximated the background value for the Pajarito Plateau, development was halted. If it did not, physical development continued until TOC content was at background level or could not be improved. Video logs were an invaluable aid in development. These were made before development to determine target intervals for more intense wire-brushing, at various stages during development if field parameters did not improve, and after development to confirm that the well was ready for Westbay™ installation.

CONSTRAINTS ON TESTING

As field methods of determining hydraulic properties of saturated materials are expensive, funding often dictated the type and duration of testing conducted. Until a separate rig was dedicated to developing and testing the wells, the drilling and Westbay™-installation schedules often dictated how much time could be spent on testing. Thus, if problems arose, re-running tests was not always possible. If the problem wasn't discovered until after the Westbay™ system was installed, re-testing was not practical.

However, hydrologic testing of the R wells has been most constrained by the hydrogeologic setting and well construction. These constraints should not be interpreted to mean that the tests were inappropriate or that the data obtained are unreliable. Rather, they are conditions that limited the testing methods that could be applied.

Hydrogeologic Constraints

Stratigraphy and depth to water are the main hydrogeologic constraints on testing. The stratigraphic sequence underlying the Pajarito Plateau is complex. Interbedded igneous and sedimentary deposits characterize the geologic column. Furthermore, the column varies considerably from place to place

(Stone et al. 2001, 69830). The variation between hard and soft materials gives rise to irregularities in borehole diameter. Washouts have been fairly common in the Puye Formation. Screens have not been placed in such intervals.

In addition to stratigraphic constraints, the regional water table lies at great depth: as much as 1178 ft below ground surface (bgs) for the wells covered by this report (Table 2). Thus, the wells must also be deep to penetrate the regional zone of saturation. Most R wells are greater than 1000 ft in depth. This depth impacts testing in different ways, depending on test method. In the case of injection tests, introduced water falls a long way before reaching the static water level for a given screen. In the case of pumping tests, pumps used must be able to lift water from such depths at a rate that stresses the saturated medium.

Well-Design Constraints

Small-diameter production casing, multiple screened intervals, screens spanning contacts between geologic units, pipe-based screens, and long filter packs are the main testing constraints associated with well design. The R wells are commonly constructed with a 4.5-in. inside diameter (I.D.) production casing. Thus, there is little room to accommodate a slugger and transducer for traditional slug tests. This small diameter also limits the size of pump that can be used, which in turn limits the pump capacity. Such limitations impact both well development and evaluation by pumping tests.

Most R wells are completed with multiple screens (Table 2). Each screen must be isolated both for development and testing. Straddle packers are readily available for shutting in individual screened intervals. However, conducting traditional slug or pumping tests in conjunction with straddle packers is difficult at best. No testing apparatus is readily available that permits interchanging transducers and pumping from considerable depth at a rate sufficient to stress a productive saturated zone, especially in the small-diameter production casing used in the R wells.

If a screen straddles a geologic contact, testing yields an average result for the two materials involved, or a result biased by the response of the more permeable material, rather than a representative hydraulic property for a single saturated material. Only one of the tests reported here involved a screen that straddles a geologic contact. R-13 was completed with a single screen set in the Puye Formation. However, the screen spanned the contact between the pumiceous and overlying fanglomerate units of the Puye. Presumably, the results of testing at R-13 represent the more permeable of the materials behind the screen, but only tests of screens dedicated to each of the units would reveal conclusively which is more permeable.

In most of the R wells, including four of the five reported on here, the uppermost screen was placed across the water table at the request of the NMED. In these cases, the upper 5 ft or so of screen is in the vadose zone, thus hindering development and ruling out testing of saturated aquifer properties. Any turbid water raised in the well during development simply drains into the unsaturated material lying behind the upper portion of the screen. Furthermore, slug or injection testing is not appropriate as these methods assume the screen is below static water level. For example, the Bouwer-Rice (1976, 64056) slug-test method cannot be used if the water level is below the top of the screen because “water would drain from the well into the vadose zone as well as the saturated aquifer” (Fetter 1994, 70942). Thus, testing of screens straddling the water table overestimates permeability because the unsaturated material takes up water faster than the saturated material.

The use of pipe-based screen introduces another constraint to testing. Injected or pumped water must move through the tortuous path presented by two layers of screen: the perforated pipe and the wire-wrap envelope. If one layer has a different open area than the other, it limits the rate at which water is delivered or extracted, thus hindering well development and yielding low test results.

Usually, the primary filter pack extends 5 ft above and below the screen and the intervals of secondary filter pack are generally also 5 ft long. Where the screen is 10 ft long, the length of filter pack is usually 30 ft or three times that of the screen. In seven of the twelve intervals tested, however, the length of filter pack has exceeded three times the length of associated screens. In some of the wells, the length of some filter packs is many times the length of the associated screen (Table 4).

Table 4
Filter-Pack Length vs. Screen Length in Wells Tested

Well (Screen)	Screen Length (ft)[a]	Filter-Pack Length (ft)[b]	Filter-Pack Length/Screen Length
R-9i (1)	10.4	19.6	1.9
(2)	10.7	18.5	1.7
R-13 [c]	60.39	86	1.4
R-19(6)	7.1	103.9	14.6
(7)	7.1	20.2	2.8
R-22(2)	41.9	69.5	1.7
(3)	6.7	49.5	7.4
(4)	6.7	22	3.3
(5)	5.0	43	8.6
R-31(3)	10	44	4.4
(4)	10	61.5	6.1
(5)	10	198.9	19.9

[a] Length of openings, not joints.
[b] Total; more than one sand size generally used.
[c] Only one screen in this well.

OVERVIEW OF TESTS

In view of the constraints described above, the aquifer properties of the saturated materials penetrated by the R wells were investigated by straddle-packer/injection and/or pumping tests (Table 5). Three of the five wells were investigated by injection tests alone (R-19, R-22, and R-31). One well was tested by both injection and pumping methods (R-9i). One well was tested by the pumping method alone (R-13). Injection tests for R-9i, screen 1 and R-22, screen 4, as well as the pumping test at R-13 were repeated.

Field and testing methods used are compatible with those recommended by the American Society for Testing and Materials (ASTM 1994, 70099, and 1996, 70100). Furthermore, the use of pressure transducers and collection of water-level measurements in both types of tests followed procedures given in Environmental Restoration (ER) Project Standard Operating Procedures ER-SOP-07.01 and 07.02, respectively. Test data were analyzed by means of commercially available software.

For a given type of test, essentially the same procedures were employed. To avoid repetition in the sections that follow, those methods are summarized once at the outset.

Table 5
Overview of Hydrologic Testing

Well (screen)[a]	Saturated Zone[b]	Geologic Unit[c]	Type of Test[d]	Analytical Method[e]	K (ft/d)	T (ft^2/d)
R-9i (1a)	U. perched	Tb	Injection/R	Bouwer-Rice	4.87	
(1b)	U. perched	Tb	Injection/R	Bouwer-Rice	3.88	
(2)	L. perched	Tb	Injection/R	Bouwer-Rice	0.11	
(1)[f]	U. perched	Tb	Pumping/D	Theis	4.75	49.4
R-13b	Regional	Tpfp	Pumping/P	Hantush-Jacob	21.4	1293.3
	Regional	Tpfp	Pumping/R	Hantush-Jacob	13.7	829.7
R-19 (6)	Regional	Tpp	Injection/R	Bouwer-Rice	1.10	
(7)	Regional	Tpp	Injection/R	Bouwer-Rice	0.73	
R-22 (2)	Regional	Tb	Injection/R	Bouwer-Rice	0.04	
(3)	Regional	Tpf	Injection/R	Bouwer-Rice	0.21	
(4a)	Regional	Tbo	Injection/R	Bouwer-Rice	0.54	
(4b)	Regiona	Tbo	Injection/R	Bouwer-Rice	0.72	
(5)	Regional	Tfo	Injection/R	Bouwer-Rice	0.27	
R-31 (3)	Regional	Tb	Injection/R	Bouwer-Rice	0.41	
(4)	Regional	Tpt	Injection/R	Bouwer-Rice	1.23	
(5)[g]	Regional	Tpt	Injection/R	Bouwer-Rice	0.75	

[a] See hydrogeology and construction diagrams for depths of screened intervals; R-13 has only 1 screen. Letters after screen number indicate test: a = initial test, b = repeat test with same design, analytical method.
[b] U. = upper, L. = lower; see hydrogeology and construction diagrams.
[c] Tb = Cerros del Rio basalt; Tpf = Puye Formation (fanglomerate); Tpfp = Puye Formation (fanglomerate and pumiceous); Tpp = Puye Formation (pumiceous); Tpt = Puye Formation, Totavi Lentil; Tbo = older basalt: Tfo = older fanglomerate.
[d] R = recovery data analyzed**;** D = drawdown data analyzed (see appendices for field-data plots).
[e] Bouwer-Rice (1976, 64056); Hantush-Jacob (1955, 70115); Theis (1935, 70102); Table 13 gives major assumptions of analytical methods used. Results are for primary analytical methods or one giving most reasonable results; see summary tables for results of comparative methods.
[f] Well was open to both upper and lower screens during test, but based on low productivity of material behind lower screen, the test essentially evaluated only that behind upper screen.
[g] Test conducted before well fully developed but not retested after second round of development.

Injection-Test Procedures

Hydraulic properties of saturated materials at four of the five wells (R-9i, R-19, R-22, and R-31) were investigated by means of injection tests. First, a target screen was isolated by straddle packers deployed inside the well casing. Then, a finite amount of water was introduced at a constant rate by means of a hose inserted into the open end of the drill rod connected to the injection assembly (Figure 2). Water moved by gravity down the rod, through the upper packer, and out of the perforated pipe in the injection assembly, through the screen, and into the saturated medium.

These are not slug tests, as the water is not introduced instantaneously. Rather, they are a hybrid type of test, necessitated by the constraints described above. Procedures used were those outlined in ER Standard Operating Procedure (SOP) ER-SOP-07.03.

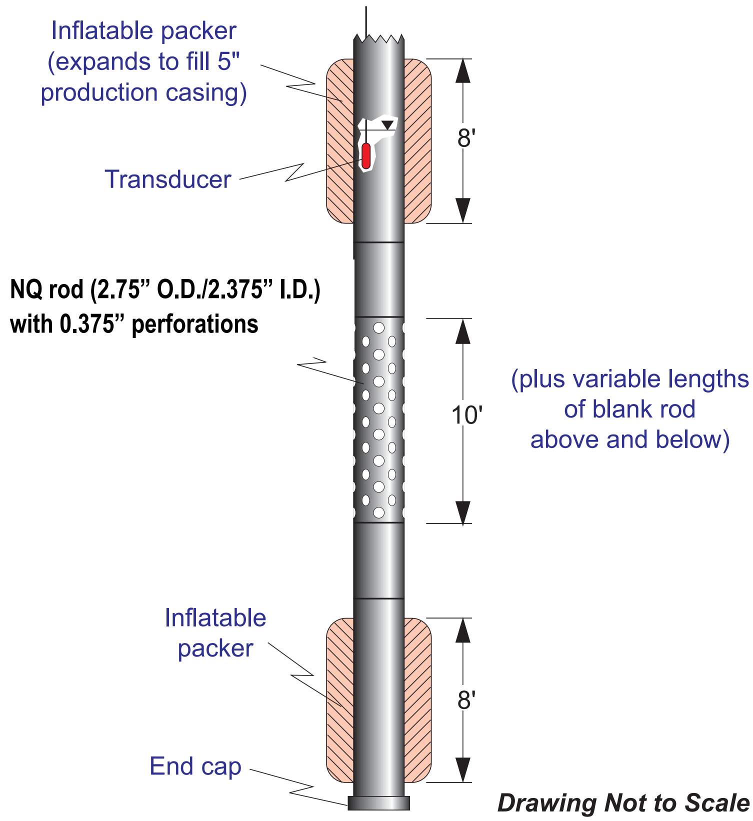

Figure 2. Straddle-packer/injection assembly

Water introduced into the wells during injection testing does not impact water quality for three reasons: (1) the water injected is drinking water from the Los Alamos municipal supply and, therefore, does not introduce contaminants; (2) the volume of water injected is small, especially when compared with the volumes added in other stages of the well installation (Table 6), so there is little dilution of natural groundwater; and (3) following testing, five times the volume of water introduced is pumped from each screened interval where there was injection to remove the foreign water. NMED's Ground-Water Quality Bureau approved the injection of municipal water for these tests without requiring the Lab to file a discharge permit.

Table 6
Water Introduced and Extracted at Wells Tested by Injection

Well	Water Added in Drilling (gal.)	Water Added in Construction (gal.)	Water Removed in Development (gal.)	Water Injected in Testing (gal.)
R-9i	Minimal[a]	? [b]	4465	701[c]
R-19	Minimal	?	~50,000	442
R-22	Minimal	42,000	34,803	440
R-31	Minimal	39,000	14,930	580

[a] Drilled by air-rotary methods.
[b] ? = not given in well completion report.
[c] Pumping test following injection test produced 4310 gal.

Straddle-packer/injection testing involved several steps:

1. Pertinent **pre-test information** was compiled and recorded.
2. The **straddle-packer/injection assembly** (Figure 2) was emplaced and inflated. Gauges on the nitrogen tank were checked frequently to ensure that the packers were holding pressure.
3. **Water level** was measured with an electric probe and the static position was recorded.
4. A **transducer** was emplaced and its position recorded. Its operation and communication with the datalogger were checked by connection to a laptop computer.
5. **Water for injection** was placed in a large open stock tank. The water was taken up by means of a hose connected to the Bean pump on the drilling rig. A hose was used to gravity-flow water into the well through drill rods connected to the injection assembly. Only municipal water was used.
6. Prior to testing, the **rate of discharge** from the injection hose was evaluated and adjusted to an appropriate value, based on yield during development.
7. A fixed volume of **water was injected** down the rod connected to the straddle-packer assembly, or water was injected over a fixed time interval.
8. The **variation in flow rate** during injection and **total volume injected** were evaluated using a flow meter (in-line between the water supply tank and the pump) and a stopwatch or watch with a second hand.
9. **Water-level rise** during injection was monitored by transducer and recorded by a datalogger.
10. **Recovery** to pre-test static water level was monitored on a laptop. When water level returned to the static position, the test was halted.
11. **Post-test data** (duration of test, volume injected, final water level, etc.) were recorded.

Following the tests, up to five times the volume of water injected was pumped out of the well to minimize the impact of introducing foreign water.

Pumping-Test Procedures

Pumping tests were conducted at two of the five wells (R-9i and R-13). Procedures used were those given in various standard texts (e.g., Driscoll 1986, 70111, or Kruseman and de Ridder 2000, 70110) and as outlined in ER-SOP-07.04.

The pumping tests involved several steps:

1. A **submersible pump** was installed.
2. An initial **static water-level** condition in the well was ensured by monitoring for an extended period after the pump was installed but prior to testing.
3. Pertinent **pre-test** information (pump type, pump depth, static water level) was recorded.
4. A pressure **transducer** was emplaced and the position recorded. Its operation and communication with the datalogger were checked by connection to a laptop computer.
5. **Barometric pressure** was recorded during the test period using the transducer.
6. The pump was turned on and the **discharge rate** was monitored by means of an in-line flow meter and stopwatch or watch with a second hand.
7. Drawdown observations were monitored with a laptop and recorded by a data logger.
8. When the drawdown seemed to be leveling off, the **pump was turned off**.
9. **Recovery** of the water level was then monitored.
10. When the pre-test static level was reached or nearly so, the **test was halted**.
11. **Post-test data** (duration of test, total volume pumped, final water level, etc.) were recorded.

Produced water was not allowed to re-enter the aquifer being tested. Rather, well discharge was collected in a large-capacity tank.

DATA ANALYSIS

Data collected in the injection and pumping tests were analyzed by various standard methods to obtain hydraulic properties. That is, plots were made showing the fit of the test data to appropriate theoretical curves. AQTESOLV[TM] for Windows (version 3.01, professional) was used to produce the plots and analyze the data from all tests. For consistency throughout the analyses, standard assumptions were made for some input parameters required by the software:

> Saturated thickness = the length of filter pack if confined, the height of water column if unconfined,
> Anisotropy ratio = 1,
> Filter-pack porosity = 0.25, and
> Well-skin radius = well-bore radius.

The software accounts for the effects of partial aquifer penetration, when specified.

Our general approach was to obtain and present the best curve match possible and then evaluate the resulting values for hydraulic parameters. Any unreasonable results are treated in the sections of this report entitled "Discussion." We analyzed the injection tests only by slug-test methods and the pumping tests only by pumping-test methods. It could be argued that the longer injection tests should be analyzed by some pumping-test methods. We did not do this for two reasons. First, although some injection tests are too long for slug tests, they are too short for pumping tests. Second, since a quasi-static water level was developed in the longer injection tests, the recovery data are comparable to those obtained when a solid slugger is withdrawn in a traditional slug test.

To avoid repetition in the text, parenthetical reference citations for the various analytical methods (that is, the years of publication and ER ID numbers) are only given in the sections below.

Analysis of Injection Tests

All analyses of injection-test data focused on the recovery portion of the water-level response. Data from each injection test were analyzed by three common slug-test methods for comparison. Although results from all three methods are included in the summary tables for the tests, only plots for the main analytical method (Bouwer-Rice) are presented in the interest of space.

Bouwer-Rice Method. For consistency, we analyzed all of the injection tests by the *Bouwer-Rice slug-test technique* (Bouwer and Rice 1976, 64056). The Bouwer-Rice method applies to partial or complete well penetration of the aquifer, unconfined or confined conditions, and application of stress by addition or withdrawal of water. Although the injection tests are not slug tests, since water is not introduced instantaneously, the water-level response is very similar to that in traditional slug tests. That is, water level rises abruptly when injection starts and falls gradually after injection stops (Figure 3). The falling limbs of the field-data plots are identical to those for traditional slug tests. Therefore, analysis of the recovery (falling-limb) data by well-established slug-test methods, such as Bouwer-Rice, is reasonable.

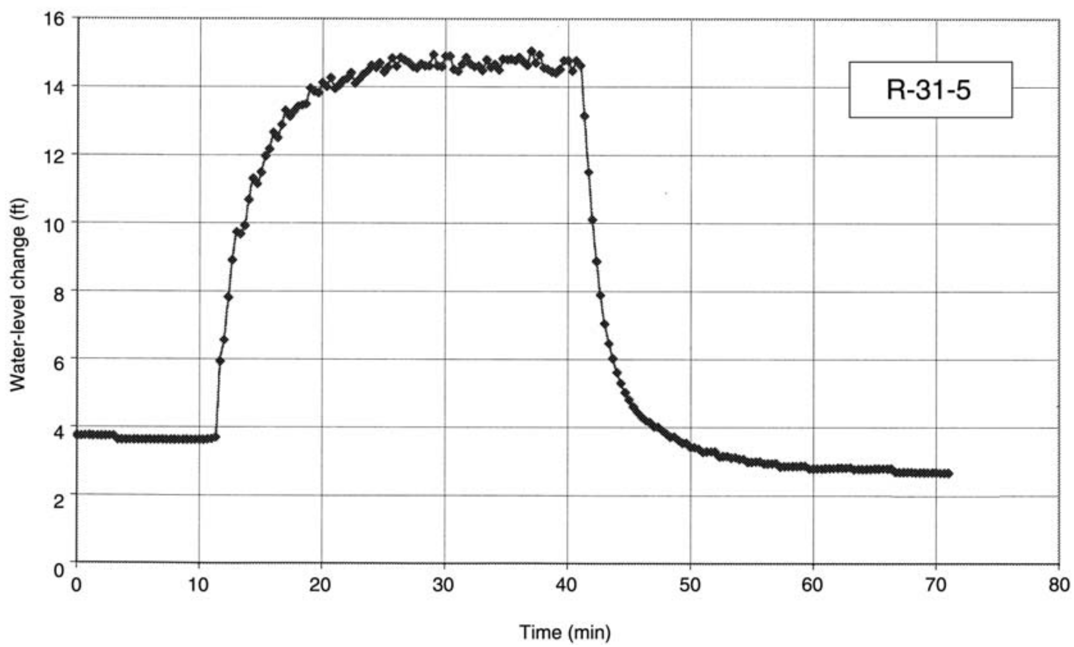

Figure 3. Typical field-data plot for the injection tests conducted

The basic parameters used in Bouwer-Rice analysis are shown in Figure 4. These include water-level change relative to static position (y), length of the well (L_w), radius of the borehole (r_b), length of the screen (L_s) and hydraulic head (H). The Bouwer-Rice slug-test procedure normally employs a solid slugger to displace a volume of water equal to the volume of the slugger. Initially, the slugger is lowered into the well until it is fully submerged. Figure 4a shows a falling-head test in which flow will be out of the well. The slugger displaces water upward in the well bore. This initial displacement above the static water level is measured as the distance y_1 (Figure 4a). The amount of displacement depends on the diameter of the well casing as well as the length and diameter of the slugger. Ideally, the value for y_1 will be several feet or more. In an effort to regain the static pre-test condition, water flows *out of* the well and into the formation through the well screen and filter pack. The distance y_1 slowly decreases back toward zero (y_0) or the same as before the slugger was inserted (Figure 4b). Figure 4c shows a rising-head test in which water or a slugger is removed and flow is from the formation *into* the well. It was not possible to perform this type of test because the wells are constructed with multiple screens.

In view of constraints imposed by well design, the Bouwer-Rice slug test procedure as described above was modified to one that is very similar to a drill-stem test commonly used in oil and gas wells (Earlougher 1977, 73478). However, the Bouwer-Rice analysis is still applicable; in fact, the Bouwer-Rice procedure is a type of drill-stem test. Water is injected by gravity into the well at a constant rate. The recorded water level initially rises very fast. However, the rate of rise eventually decreases, and water level reaches a new static equilibrium in response to the constant inflow rate (Figure 3). This new static level is located some distance above the initial static water level and the change corresponds to y_1 in Figure 4a. When water injection is suddenly stopped, the water level in the well immediately starts to fall. The injection tests performed are analogous to an ideal Bouwer-Rice slug test because a new static equilibrium was achieved before injection ceased. Results of these injection tests probably represent a lower limit of values for hydraulic conductivity as they characterize conditions in the disturbed portion of the formation near the well.

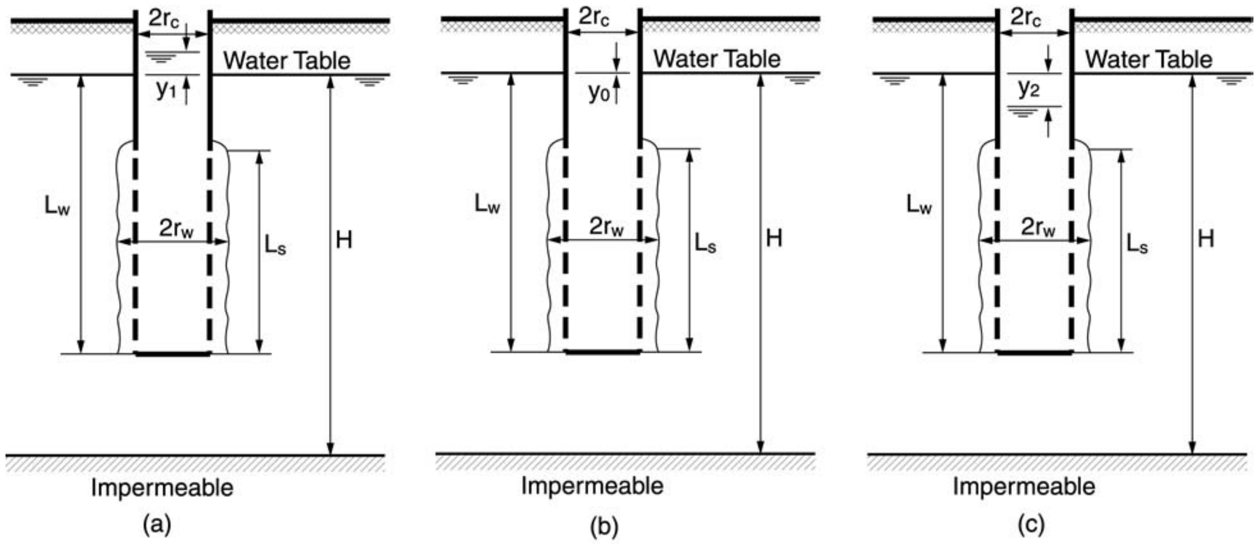

Figure 4. Relationship of Bouwer-Rice parameters to water level in well for different test types (modified from Bouwer 1978, 73678); (a) slug-injection or falling-head test (flow is out of well), (b) static equilibrium, and (c) slug-withdrawal or rising-head test (flow is into well)

Bouwer-Rice plots can consist of two straight-line segments followed by a curve deviating from the second straight line (Fetter, 1994, Figure 7.27). In such cases, the first straight line is short and represents the filter pack. The second straight line is longer and represents the saturated material tested. Beyond the second straight line segment the plot curves upward, owing to the expansion of the injected water mound. The result is a concave-upward plot.

Cooper-Bredehoeft-Papadopulos (C-B-P) Method. For comparison, injection-test data were also analyzed by the *C-B-P method* (Cooper et al. 1967, 70108). The C-B-P method assumes complete aquifer penetration, confined hydraulic condition, and application of stress by either addition or withdrawal of water. A drawback to this method is that a storativity (S) value is required. The analysis can be constrained to a specified value for S or allowed to float as the plot is matched to the theoretical curve. If a reasonable S value is used, results obtained by the C-B-P method should be similar to those yielded by the Bouwer-Rice analysis. For the tests reported, results obtained by the C-B-P method are generally comparable to those obtained by the Bouwer-Rice method, but data plots for most tests poorly match the theoretical curve. Results obtained by the C-B-P method are included in the summary tables for the tests for comparison.

Hvorslev Method. All injection tests were also analyzed by the *Hvorslev method* (Hvorslev 1951, 70101) for further comparison. The Hvorslev method assumes partial aquifer penetration, unconfined or confined conditions, and application of stress by either addition or withdrawal of water. Results obtained by the Hvorslev method are generally comparable to those yielded by the Bouwer-Rice and C-B-P methods. Values are included in the summary tables for the tests for comparison.

Analysis of Pumping Tests

Both pumping tests were initially analyzed by the *Theis method* (Theis 1935, 70102). For comparison, data were also analyzed by alternative methods suggested by the curve match for the Theis analysis. For example, we analyzed data from the pumping test at R-9i by both the Theis and *Neuman method*

(Neuman 1975, 73479). Data from the other well tested by pumping (R-13) were analyzed by the Theis and *Hantush-Jacob methods* (Hantush and Jacob 1954, 70115). Results of analysis by all methods are given in the summary tables for the pumping tests, unless a given method yielded questionable results. Plots for all acceptable analyses accompany the summary tables.

Although AQTESOLV™ automatically provides a storativity value for any analysis of pumping-test data, such a determination is not possible from single-well tests as reported here. Therefore, no results are listed for this parameter in the summary tables for the pumping tests conducted.

WELL R-9i

R-9i is located beside regional well R-9 on the south bank of Los Alamos Canyon, 0.3 mi west of the White Rock “Y” (Figure 1). During the drilling of regional well R-9 by the casing-advance method, two perched zones of saturation were encountered in the Cerros del Rio basalt (Broxton et al. 2001, 71251). As these zones were sealed off to protect the regional aquifer while R-9 was drilled to TD, R-9i, was installed beside R-9 to monitor the quality of these perched waters (Broxton et al. 2001, 66600). Well R-9i was drilled by air-rotary, casing-advance methods to a total depth (TD) of 322 ft. The well was completed with two screened intervals in the Cerros del Rio basalt (Figure 5).

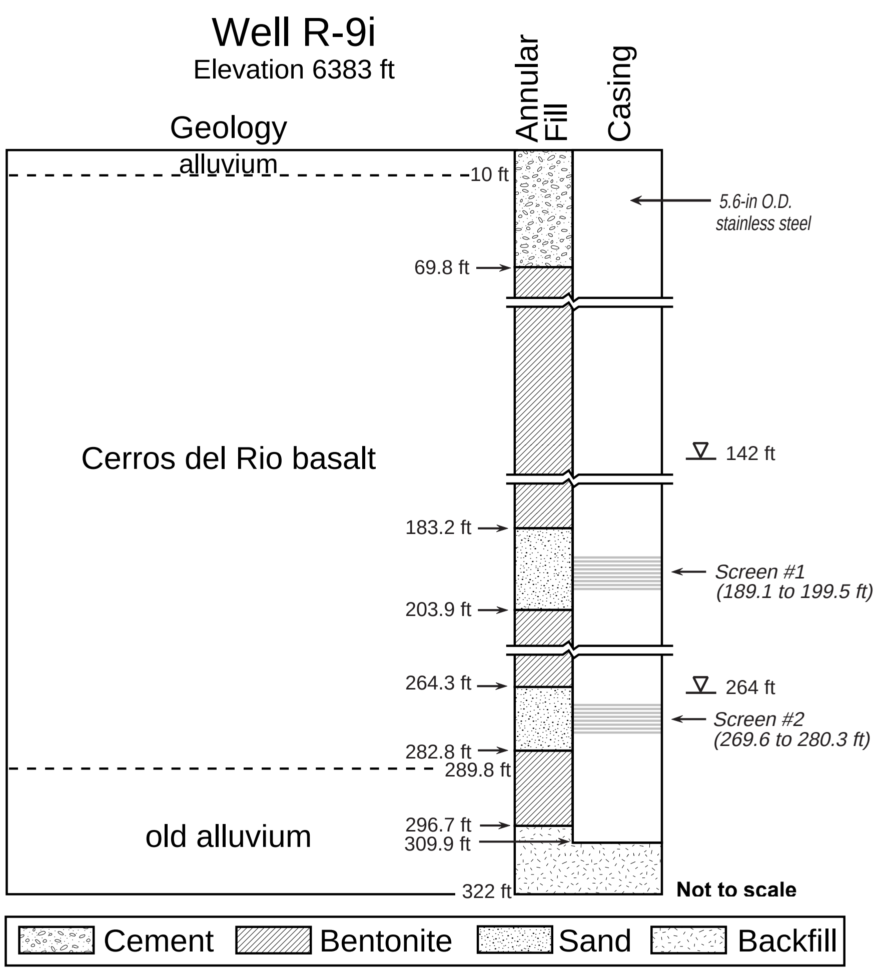

Figure 5. Hydrogeology and construction of R-9i

Hydrogeology

Geologic units penetrated by well R-9i are shown in Figure 5. The same perched zones of saturation seen in well R-9 were encountered in R-9i. Water was first recognized in the borehole at a depth of 186 ft in fractured basalt. Ultimately, the water level rose to a depth of 142 ft bgs. Such a water-level rise often indicates confined conditions. While each saturated nonvertical fracture is a miniature confined system, the rise is more likely a result of the basalt being saturated below the shallower depth and (1) water simply entered the hole too slowly to be recognized during drilling or (2) no water-bearing fractures were penetrated above a depth of 186 ft. Available head data obtained during drilling suggest a downward vertical gradient, as expected for perched saturation, thus ruling out confinement.

Injection Tests

Injection tests were attempted for both screened intervals in well R-9i (Table 7). The lower interval (screen 2) was tested first. However, this zone was so tight that within 2 min injected water came out of the top of the rod connected to the packer assembly. Injection was halted and recovery data were collected. Next, the packers were moved to the upper interval (screen 1), and two injection tests were performed there. Test design and results are summarized in Table 7. Analyses of injection-test data from R-9i are shown in Figures 6 and 7. Field and analytical data are given in Appendix A.

Table 7
Summary of Injection Testing at R- 9i

Screen #	**1**	**2**
Geologic Unit[a]	Tb	Tb
Screened Interval (ft)[b]	189.1–199.5	269.6–280.3
Screen Length (ft)[b]	10.4	10.7
Saturated thickness (ft)	61.9	18.8
Test Design		
Pre-Test Water Level (ft)[c]	141	141
Average Injection Rate (gpm)[d]	a) 12 b) 19	19
Injection-Rate Variation (%)	<10	<10
Injection Period (min)	a) 10 b) 29	2
Volume Injected (gal)	a) 120 b) 551	30
Conducted by[e]	SM/WS	SM/WS
Date	4/10/00	4/10/00
Comments:	Repeat test run	Water overflowed drill rod
Test Results		
Analyzed by[e]	SM	SM
Analytical Method	Bouwer-Rice, C-B-P, Hvorslev	Bouwer-Rice, C-B-P, Hvorslev
Hydraulic Conductivity (ft/d)[f]	a) 4.87 3.71 4.57	0.11 0.18 0.12
	b) 3.88 3.07 3.46	
Comments:	Test near ideal	—

[a] Tb = Cerros del Rio basalt.
[b] For open interval, not screen joints.
[c] Depth bgs for packed-off interval, not well.
[d] Determined by flowmeter and watch with second hand; a, b refer to initial and repeat tests throughout table.
[e] SM = S. McLin.
WS = W. Stone,
[f] Results are for Bouwer-Rice, C-B-P, Hvorslev, respectively.

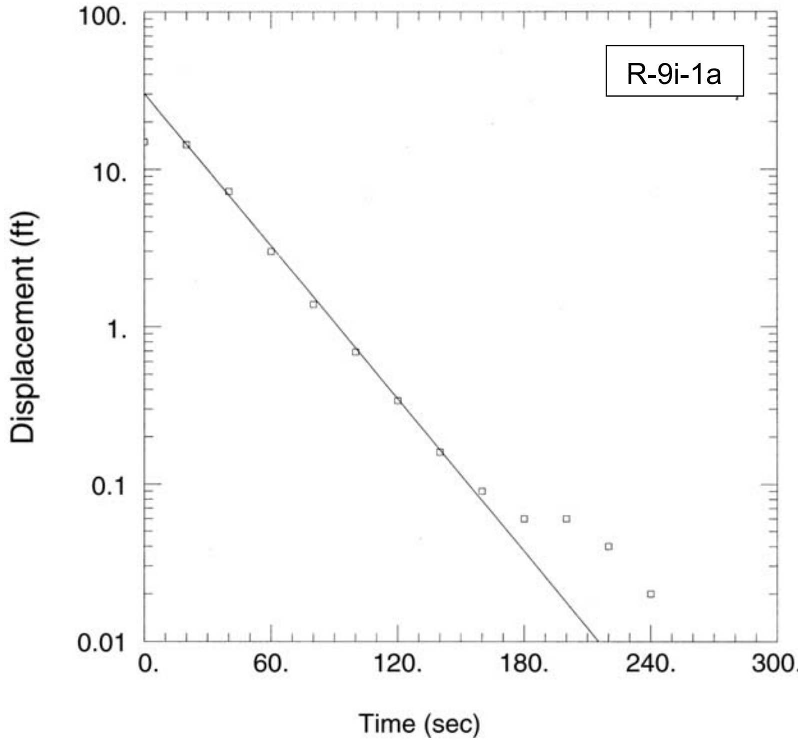

Figure 6. Bouwer-Rice analysis of injection-test recovery data for R-9i, screen 1a

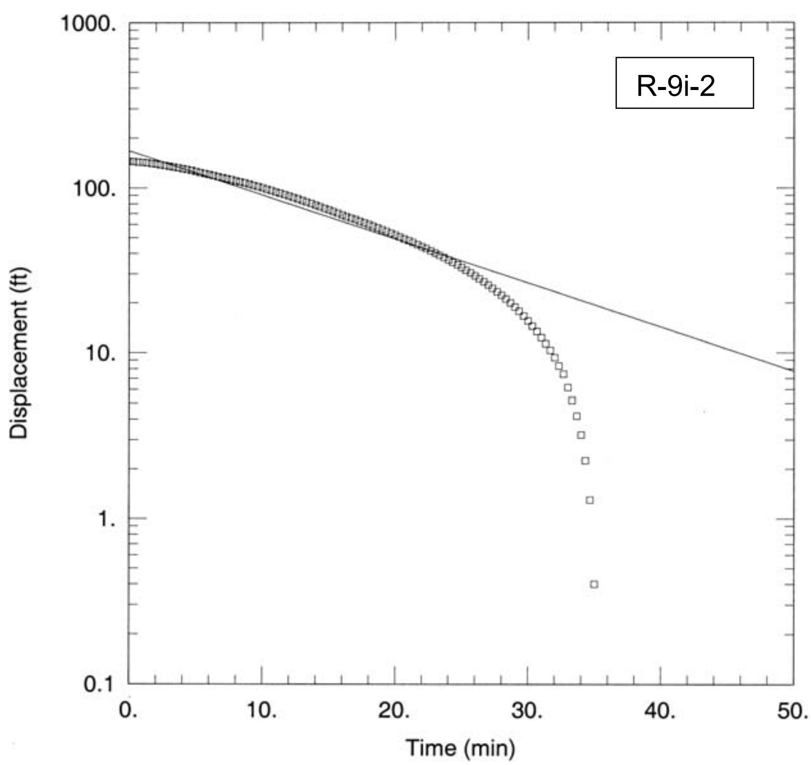

Figure 7. Bouwer-Rice analysis of injection-test recovery data for R-9i, screen 2

Pumping Test

A short-term pumping test (lasting about 7 hrs) was also conducted in well R-9i using a small submersible pump set inside the well casing. During this test, both screens were open. However, as shown by the injection tests, the hydraulic conductivity of material behind screen 1 is so much greater than that behind screen 2 that most of the pumped water came from screen 1, and the hydraulic conductivity (K) for the test represents the undisturbed formation that surrounds screen 1. Test design and results are summarized in Table 8. Analyses of pumping-test data are shown in Figures 8, 9, and 10. Field and analytical data are presented in Appendix A.

Table 8
Summary of Single-Well Pumping Test at R-9i

Geologic Unit	Cerros del Rio basalt
Screened Interval (ft)[a]	189.1-199.5
Screen Length (ft)[a]	10.4
Saturated Thickness (ft)	61.9
Test Design	
Pre-Test Water Level (ft)[b]	141
Pump Type	10 hp submersible
Depth of Pump Intake (ft)	183
Average Pumping Rate (gpm)[c]	15.41
Pumping Period (hrs)	7
Volume Pumped (gal.)	4500
Conducted by[d]	SM
Date	4/11/00
Comments: Well also open to deeper unproductive zone (screen #2), but test presumably evaluated material behind upper screen (#1).	
Test Results	
Analyzed by[d]	SM
Analytical Method	Theis Neuman (early) Neuman (late)
Transmissivity (ft^2/d)[e]	49.4 315.3 13.2
Hydraulic Conductivity (ft/d)[f]	4.75 30.3 1.3
Storativity	Not valid from single-well tests
Comments: Theis results comparable to injection test results	

[a] Length of open interval, not screen joints (screen #1).
[b] Composite value with well open to both screens.
[c] Determined by flowmeter and watch with second hand.
[d] SM = S. McLin.
[e] Results are for Neuman (early data) and Neuman (late data) respectively.
[f] Derived from transmissivity, using screen length because of shortness of test.

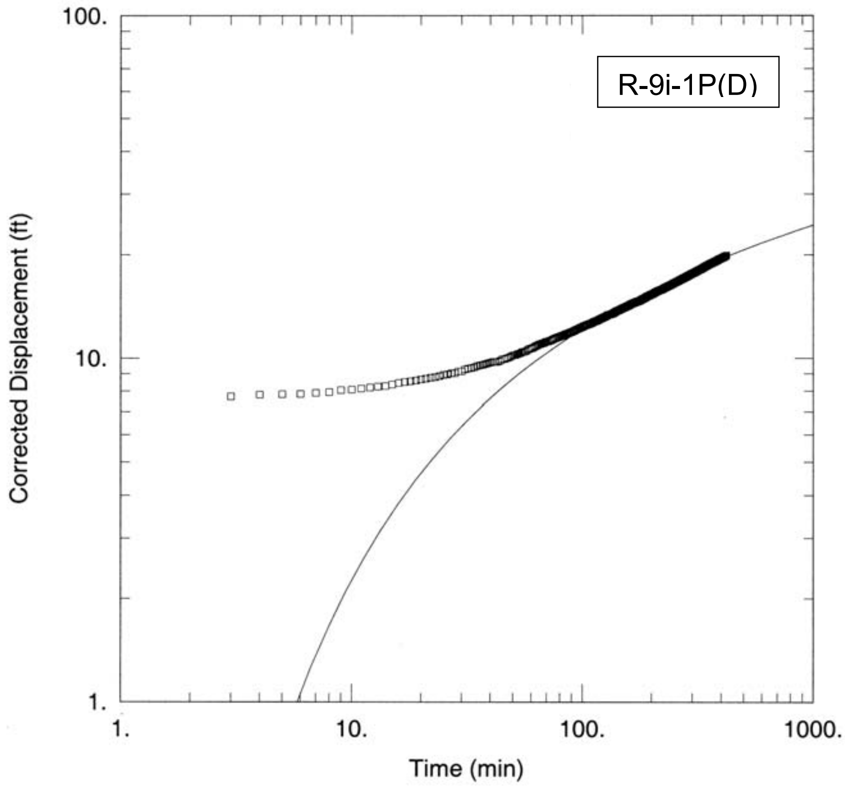

Figure 8. Theis analysis of pumping-test drawdown data for R-9i, both screens

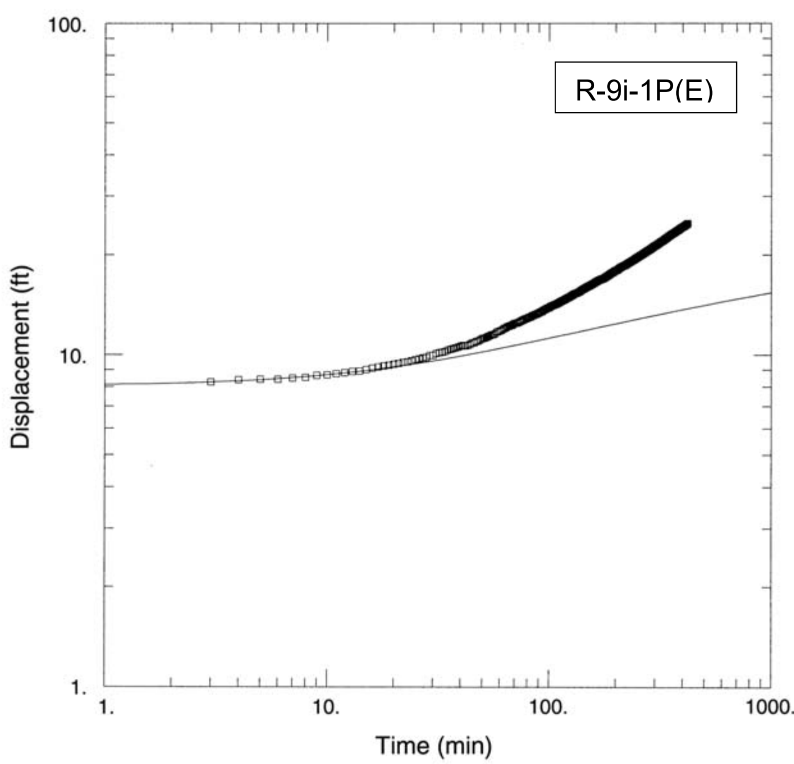

Figure 9. Neuman analysis of early pumping-test drawdown data for R-9i, both screens

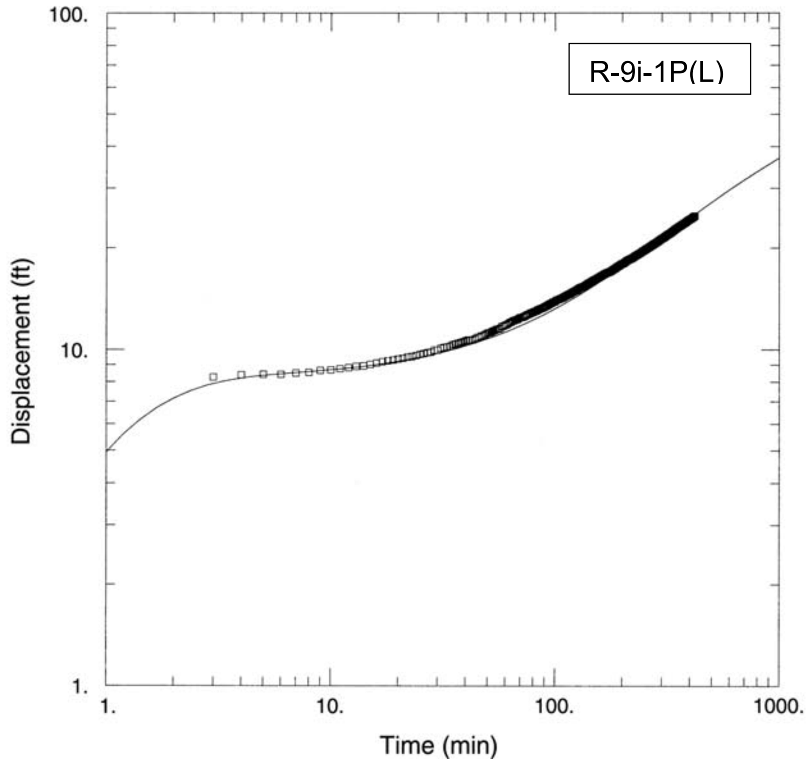

Figure 10. Neuman analysis of late pumping-test drawdown data for R-9i, both screens

Discussion

Injection Tests. Two tests were conducted for screen 1. During the first test (R-9-i-1a), water level dropped sharply in the midst of injection (the double-peak curve at the left in Appendix A-1) because of a brief cessation in water flow. No such interruption occurred during a repeat test (R-9i-1b), conducted with a greater injection rate and time.

Water injected at screen 2 quickly rose to the surface. Although Figure 5 shows a static water level for the lower perched zone of 264 ft bgs, a water-level depth of only 141 ft was measured with the packers set on that zone prior to testing. This discrepancy is the result of the hole being open to both zones before the packers were set at the lower screen and the water level did not drop to a position appropriate for the lower zone because of its low permeability. Thus, water remained at the composite level and a rise of only 141 feet was sufficient to cause water to overflow the rod connected to the injection assembly.

Pumping Test. Inasmuch as the lower screened interval was tight, it was reasoned that pumping the well when it was open to both screens would in fact test mainly the upper productive interval. Results are not the same as if only screen 1 were tested by pumping. However, as screen 2 was nonproductive, the test probably gives order-of-magnitude results for the basalt in screen 1.

Analysis/Injection Tests. The water-level response to injection at screen 1 (Appendix A-1) is similar to that in traditional slug tests. Therefore, we analyzed injection-test data for well R-9i, screen 1 by the Bouwer-Rice slug technique. The Bouwer-Rice plot for the initial injection test (R-9i-1a) is shown in Figure 6. The linear portion of the plot (i.e., the first 150 seconds) covers most of the data points collected and is the valid part of such plots. The upward turn of the plot after that is a typical Bouwer-Rice response. Bouwer-Rice analysis yielded a K of 4.87 feet per day (ft/d). The repeat test reproduced the first test with some deviation in the linear portion of the curve and yielded a K of 3.88 ft/d.

For comparison, we also analyzed injection test data for screen 1 by the C-B-P and Hvorslev slug test methods. C-B-P analysis yielded a K of 3.71 ft/d for the initial test, when S was constrained to a value of 5×10^{-5}, and a K of 3.07 ft/d for the repeat test with the same value for S. The Hvorslev analysis yielded a K of 4.57 ft/d for the initial test and 3.46 ft/d for the repeat test. Results obtained by both of these additional methods are comparable to those for Bouwer-Rice analysis.

Injection-test data for R-9i screen 2 were also analyzed by the Bouwer-Rice method (Figure 7). The figure shows an abrupt and steep downward curvature after the linear portion of the water-level decay plot. This shape sometimes results when pre-test water level is slightly higher than the static position. However, there is no indication of a higher water level on the field plot (Appendix A-4) and the reason for the response is unknown. Bouwer-Rice analysis yielded a K of 0.11 ft/d for the basalt behind the lower screen.

For comparison, we also analyzed test data from screen 2 by the C-B-P and Hvorslev methods. C-B-P analysis gave a K of 0.18 ft/d, when S was fixed at 5×10^{-6}, while analysis by the Hvorslev method gave a K of 0.12 ft/d. Results from these methods of analysis are comparable to those from Bouwer-Rice analysis.

Analysis/Pumping Test. Drawdown data from the pumping test at R-9i were analyzed by two different methods. Initially, we used the Theis method which yielded a T value of 49.4 ft^2/d (K = 4.75 ft/d). The shape of the plot in the Theis analysis (Figure 8) suggested that application of the Neuman method for a phreatic aquifer was warranted. Thus, we also analyzed both early- and late-time drawdown data by the Neuman method. Analysis for early-time data is shown in Figure 9 and suggests that T = 315.3 ft^2/d (K = 30.3 ft/d). These results are an order of magnitude greater than those for Bouwer-Rice analysis of the injection tests. When a reasonable curve match was obtained, the associated S value was unreasonable, and when S was constrained to a reasonable value, the curve match was poor. Analysis of late-time data is shown in Figure 10 and suggests that T = 13.2 ft^2/d (K = 1.3 ft/d). These results are the same order of magnitude as the Bouwer-Rice results. However, although the late-time data fit the theoretical curve extremely well, specific yields obtained are too high, casting further doubt on the T value (Appendices A-10 and A-11). Some difference in anisotropy may be unaccounted for in the analysis. Furthermore, using the pumping well as the observation well is not ideal.

WELL R-13

R-13 is located in Mortandad Canyon, just west of the eastern Laboratory boundary (Figure 1). Well R-13 was drilled to a TD of 1133 ft within the Puye Formation and completed with a single 60-ft-long screen placed 125 ft below the regional water table within the Puye (Figure 11).

Hydrogeology

Geologic units penetrated by well R-13 are shown in Figure 11. No perched water was detected. The regional water table was encountered at a depth of 834 ft within the Puye Formation. The single screen straddles the contact between the typical Puye fanglomerate and the underlying pumiceous Puye.

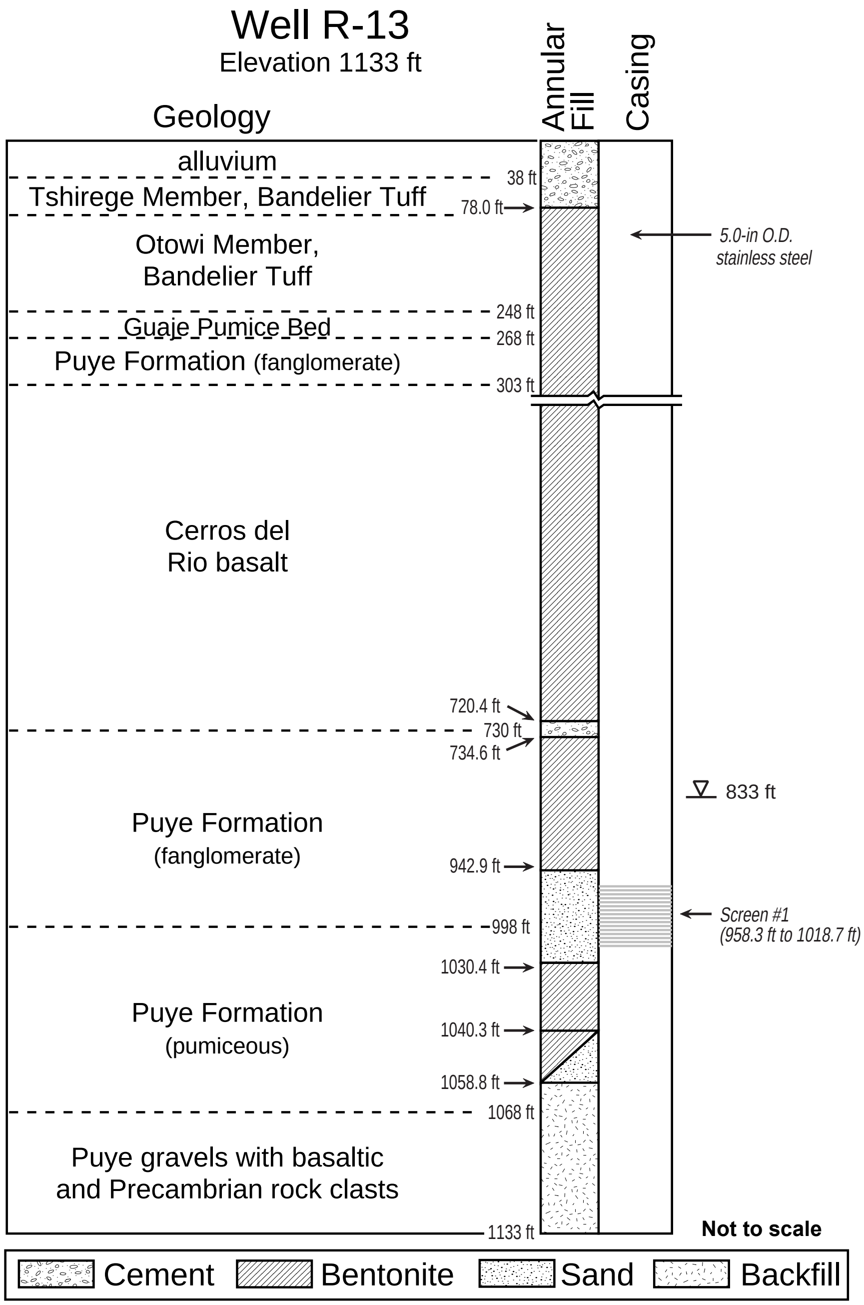

Figure 11. Hydrogeology and construction of R-13

Pumping Test

Two short single-well pumping tests were conducted at R-13 using a submersible pump inside the well casing. As drawdown and recovery data from the second (repeat) test were more uniform, it is the only one analyzed. Test design and results are summarized in Table 9. Analyses of the test data by the Hantush-Jacob method are shown in Figures 11 and 12. Field and analytical data for the repeat test are given in Appendix B.

Table 9
Summary of Single-Well Pumping Tests at R-13

Geologic Unit	Puye Formation
Screened Interval (ft)[a]	958.3–1018.7
Screen Length (ft)[a]	60.4
Saturated Thickness (ft)	87.5
Test Design	
Pre-Test Water Level (ft)	833
Pump Type	10 hp submersible
Depth of Pump Intake (ft)	931.34
Average Pumping Rate (gpm)[b]	a) 18.9 b) 19
Pumping Period (min)	a) 22 b) 12
Volume Pumped (gal.)	a) 430 b) 190
Conducted by[c]	WS
Date	10/31/01
Comments: Pumping rate apparently not enough to stress aquifer; water level during first test erratic	
Test Results	
Analyzed by[c]	SM
Analytical Method	Hantush-Jacob
Transmissivity (ft^2/d)	a) not analyzed b) 1293.3 (pumping), 829.7 (recovery)
Hydraulic Conductivity (ft/d)[d]	b) 21.4 (pumping), 13.7 (recovery)
Storativity	Not valid from single-well tests
Comments: Recovery analysis more reliable	

[a] Length of open interval, not screen joints.
[b] Determined by flowmeter and stopwatch; a and b refer to initial and repeat tests throughout table.
[c] WS = W. Stone, SM = S. McLin.
[d] Derived from transmissivity, using screen length because of shortness of test.

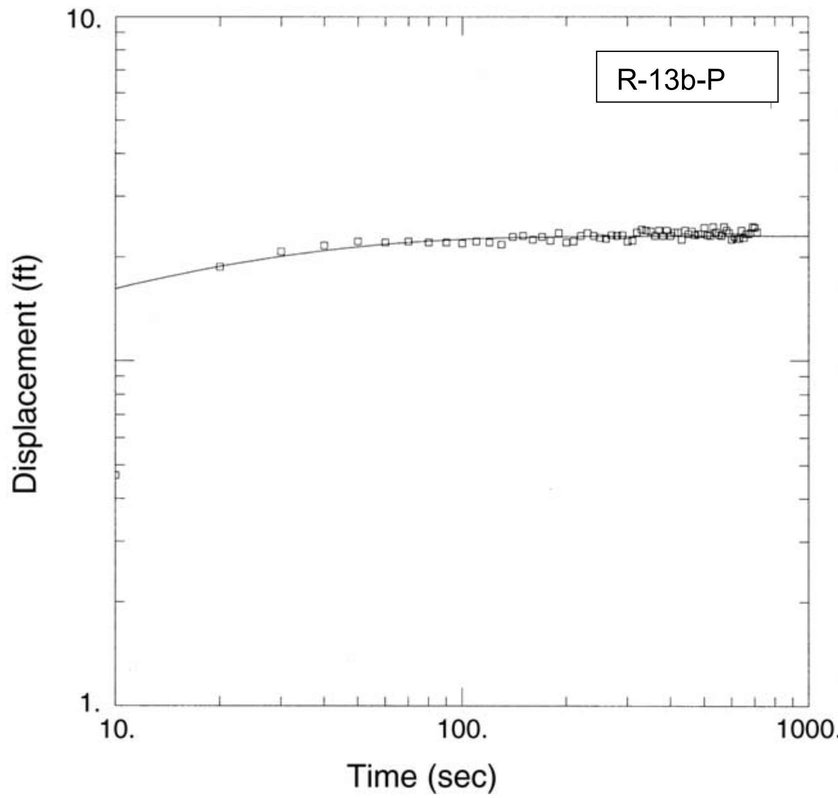

Figure 12. Hantush-Jacob analysis of pumping-test recovery data for R-13b

Discussion

Test. Because R-13 was constructed with a single screen situated below the water table, it provided an excellent opportunity for evaluating aquifer properties by means of a traditional single-well pumping test. Two tests were conducted. In the first test (R-13a), water level was erratic. In the second test (R-13b), after an initial drawdown of about 2.5 ft, the water level declined very gradually (Appendix B-1). Water level oscillated at this position on the order of 0.1 to 0.3 ft. This drawdown, in response to running a 10-horsepower (hp) pump at a maximum discharge rate of 19 gallons per minute (gpm), suggests that a higher discharge rate, and perhaps a larger pump, are required to stress the regional aquifer at this location.

Analysis. As water level during the first test was erratic and the recovery curve had only a few data points, it was not analyzed. Both drawdown and recovery data for the repeat pumping test (R-13b) were more uniform and thus were analyzed. Data analysis by the Theis method suggested leaky aquifer conditions with partial penetration. Therefore, data were analyzed by the Hantush-Jacob technique for a leaky aquifer. While the duration of pumping was not optimal, analysis of pumping data yielded a T value of 1293.3 ft^2/d (K = 21.4 ft/d) and analysis of recovery data yielded a T value of 829.7 ft2/d (K = 13.7 ft/d). These values are consistent with the productivity of this zone.

As the screen straddles the contact between the pumiceous and fanglomerate units of the Puye Formation, the test result cannot be assigned to either one of these materials. The test yielded an average result that probably overestimates the permeability of one unit and underestimates the permeability of the other unit.

WELL R-19

Well R-19 is located on the mesa between Threemile and Pajarito Canyons in TA-36 (Figure 1). It was drilled to a TD of 1902 ft, but the final depth is 1885 ft in the Puye Formation because of sloughing in of the borehole (Broxton et al. 2001, 66603). It was completed with seven screens: two in possible perched zones, one across the water table, and four within the regional zone of saturation (Figure 13).

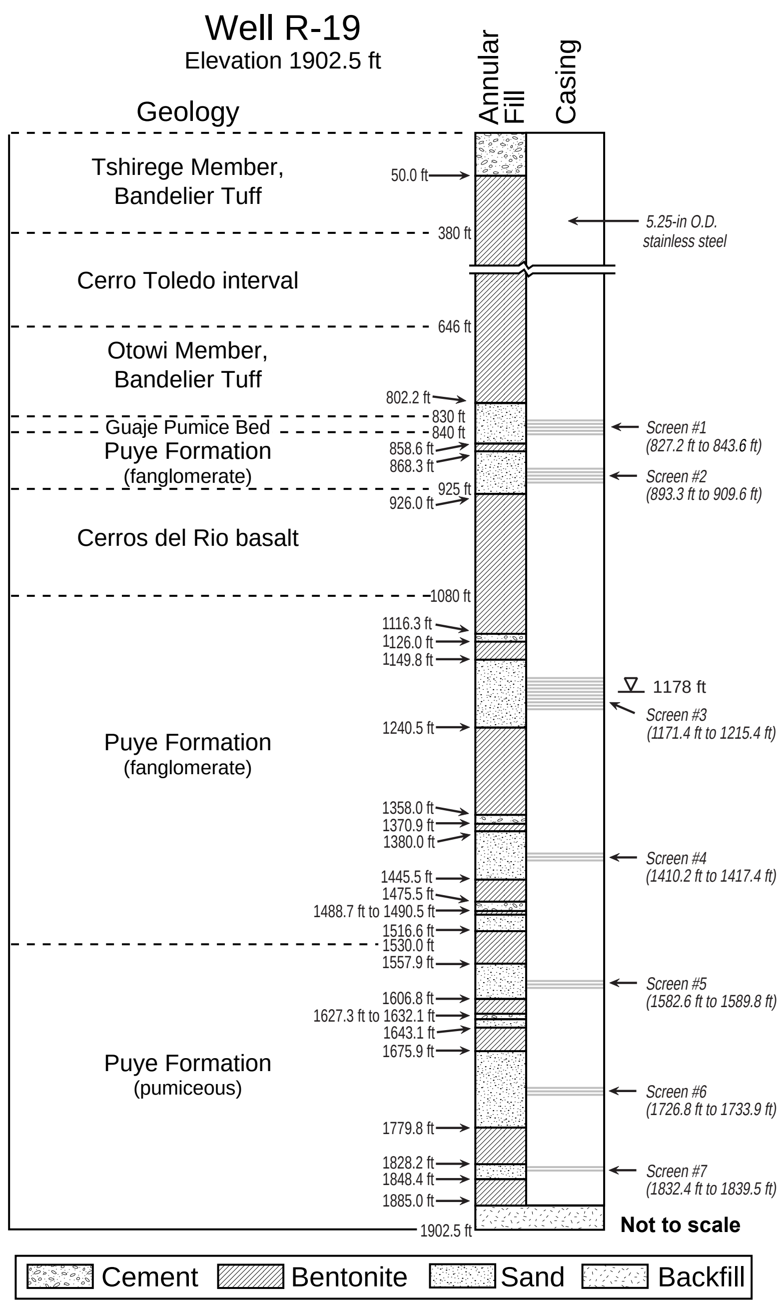

Figure 13. Hydrogeology and construction of R-19

Hydrogeology

Geologic units penetrated by well R-19 are shown in Figure 13. Two possible zones of perched saturation were encountered at depths of 834 to 840 ft in the Guaje Pumice Bed and at 894 to 912 ft in the Puye Formation. The regional water table was encountered at a depth of 1178 ft within the Puye Formation. Two head measurements made during testing indicate that a downward vertical gradient exists in the regional zone of saturation at well R-19.

Injection Tests

The lowermost two screened intervals (screens 6 and 7) were tested at well R-19. Test design and results are summarized in Table 10. Analyses of injection-test data are shown in Figures 14 and 15. Field and analytical data are given in Appendix C.

Table 10
Summary of Injection Testing at R-19

Screen #	**6**	**7**
Geologic Unit[a]	Tp	Tp
Screened Interval (ft)[b]	1726.8-1733.9	1832.4-1839.5
Screen Length (ft)	7.1	7.1
Saturated Thickness (ft)	103.9	20.2
Test Design		
Pre-Test Water Level (ft)[c]	1177	1774
Average Injection Rate (gpm)[d]	11.8	14.6
Injection-Rate Variation (%)	<10	<10
Injection Period (min)	10	22
Volume Injected (gal)	120	322
Conducted by[e]	NT	NT
Date	7/27/00	7/27/00
Comments	—	—
Test Results		
Analyzed by[e]	SM	SM
Analytical Method	Bouwer-Rice C-B-P Hvorslev	Bouwer-Rice C-B-P Hvorslev
Hydraulic Conductivity (ft/d)[f]	1.10 1.21 1.36	0.73 1.30 1.08
Comments	Analytical plots reasonable	

[a] Tp = Puye Formation.
[b] For open interval, not screen joints.
[c] Depth below ground surface for packed-off interval, not well (composite static water-level depth for well = 1179 ft).
[d] Determined by flowmeter and stopwatch or watch with second hand.
[e] NT = Neal Tapia, SM = S. McLin.
[f] Results are for Bouwer-Rice, C-B-P, and Hvorslev, respectively.

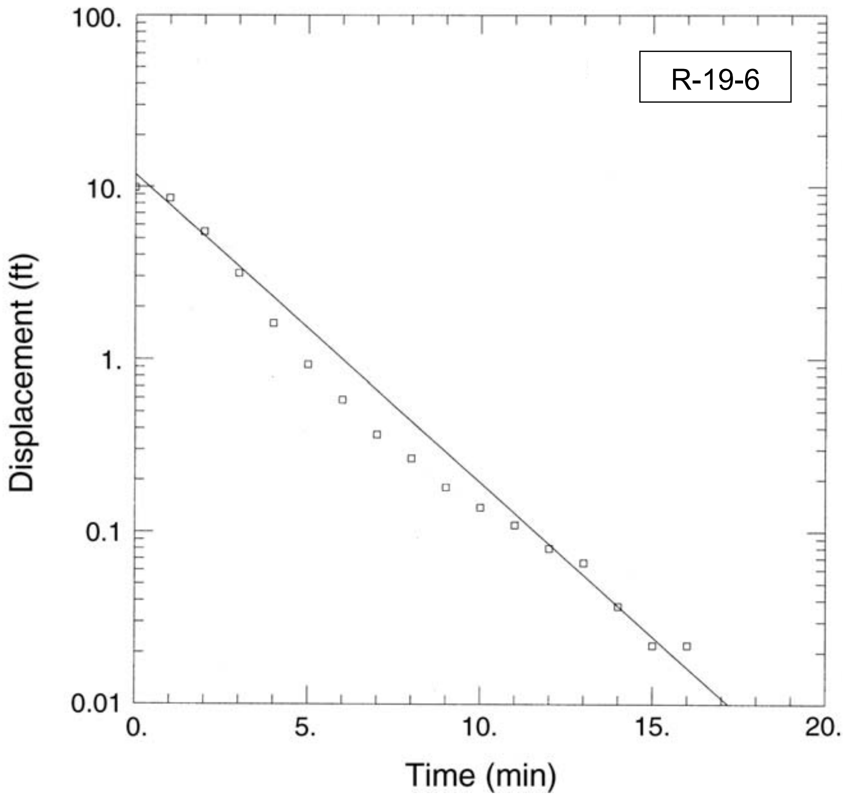

Figure 14. Bouwer-Rice analysis of injection-test recovery data for R-19, screen 6

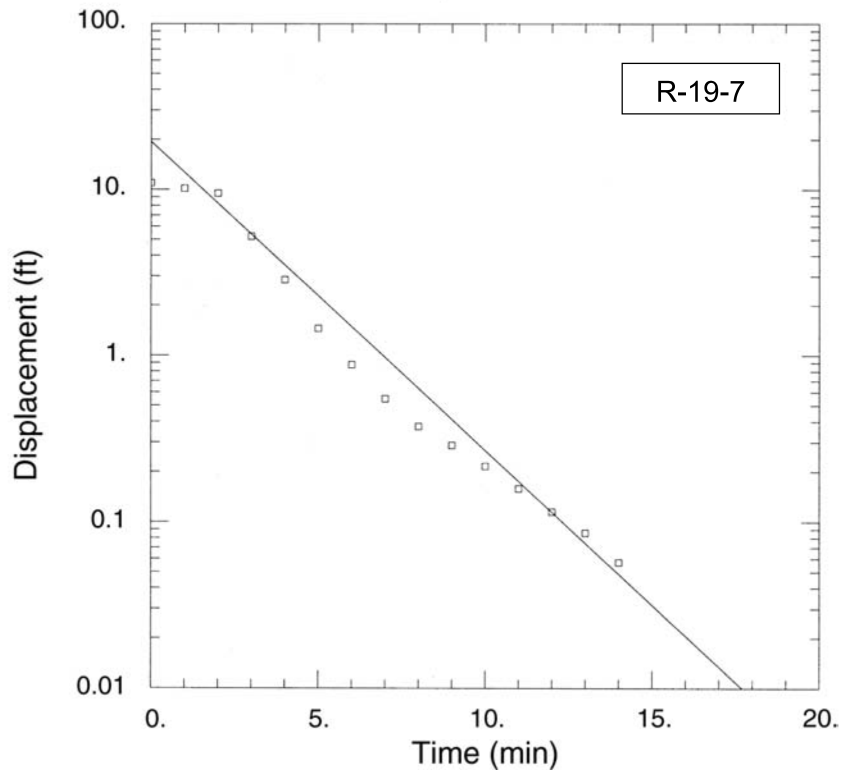

Figure 15. Bouwer-Rice analysis of injection-test recovery data for R-19, screen 7

Discussion

Tests. Screen 3 at R-19 straddles the water table, so testing by injection was not appropriate. As both screens 4 and 5 were initially thought to be located within the fanglomerate unit of the Puye Formation, only one (screen 5) was tested. (Further geologic analysis has shown that only screen 4 is in the fanglomerate and screen 5 is in the newly recognized pumiceous unit of the Puye Formation.) However, the test of screen 5 was unsuccessful because water depth during injection exceeded the capacity of the transducer. If the material behind a screen does not readily take up the injected water, the water level can quickly rise above the rated depth of the transducer, rendering it inoperable. When testing was attempted at screen 5, water level in the straddle-packer/injection apparatus and drill rods rose rapidly. After 30 gal. of water were injected, the capacity of the transducer was exceeded so testing was abandoned. Nonetheless, testing at well R-19 successfully characterized the newly recognized lower pumiceous unit in the Puye Formation, accessible in screens 6 and 7.

Analysis. As plots for the Bouwer-Rice analysis of data for tests of screens 6 and 7 are somewhat S-shaped, we passed a line through the data, approximating a straight-line fit. The results from the injection tests at screen 6 and 7 are similar as they evaluated similar geologic material (pumiceous Puye).

Bouwer-Rice analysis of data for the injection test at screen 6 yielded a K of 1.10 ft/d (Table 10). Analysis of the data by the C-B-P method gave a K of 1.21 ft/d, with $S = 5 \times 10^{-5}$; however, the data fit the theoretical curve poorly. Hvorslev analysis of data from the test at screen 6 resulted in a K of 1.36 ft/d. Results for the three methods are comparable.

Results of analysis of the test at screen 7 by all three methods are also similar. Bouwer-Rice analysis of the data from the test at screen 7 yielded a K of 0.73 ft/d. Although data fit the theoretical curve poorly, analysis by the C-B-P method gave a K of 1.30 ft/d. Hvorslev analysis gave a K of 1.08 ft/d.

WELL R-22

Well R-22 is located east of MDA-G in Technical Area (TA)-54 on the mesa between Cañada del Buey and Pajarito Canyons (Figure 1). It was drilled by open-hole methods to a TD of 1489 ft in the Santa Fe Group (Ball et al. 2001, 71471). The well was completed with five screens: one at the water table and four within the regional zone of saturation (Figure 16).

Hydrogeology

Geologic units penetrated by well R-22 are shown in Figure 16. No perched water was encountered at this location. The regional water table was penetrated at a depth of 883 ft in the Cerros del Rio basalt (Ball et al. 2001, 71471). Of the four screens below water table, two provide access to basalt, one is situated in Puye Formation fanglomerate, and one is situated in older fanglomerate. Head measurements for each screened interval during testing indicate the vertical gradient is downward at R-22.

Injection Tests

Straddle-packer/injection tests were attempted at each of the screened intervals below the water table, that is, screens 2 through 5. During the test at screen 3, the rod to which the packer assembly was attached dropped 4.8 in. and stripped the coating off the transducer cable, so the test had to be halted. To make the best use of rig time while the cable was being repaired at the drilling yard, the packer assembly was moved down to screen 4 and a static water level was determined. When the cable had been repaired and returned to the site, testing resumed with screen 4. A repeat test of screen 4 (R-22-4b) with the same injection rate and time was also run for comparison. Finally, screen 5 was tested. Test design and results for all tests are summarized in Table 11. Analyses of injection-test data are shown in Figures 17 through 20. Field and analytical data are given in Appendix D.

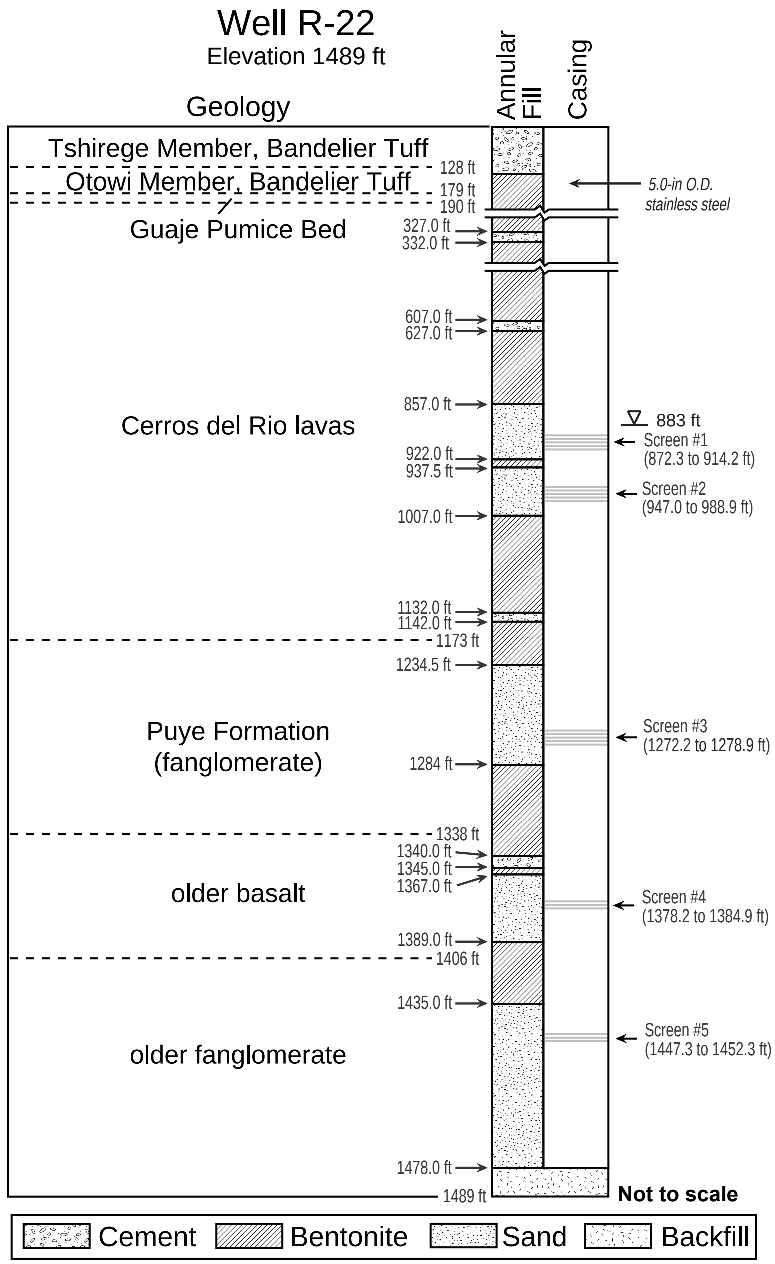

Figure 16. Hydrogeology and construction of R-22

Discussion

Tests. During injection tests of screens 2 and 3 at R-22, the peak water level exceeded the depth capacity of the transducer. Thus, plots in the appendix show a horizontal line for maximum water level instead of a peak (Appendix D-1 and D-5). As sufficient water-level observations had been made before capacity was exceeded, a procedure for reconstructing the peaks for these plots was successfully applied and the test data were analyzed.

A repeat injection test was conducted for the material behind screen 4 at R-22. Results were reproduced as the hydraulic-conductivity value obtained is of the same order of magnitude as that for the initial test (Table 11).

The cause of a jump in the water-level plot during testing of screen 5 (near the end of the recovery curve in Appendix D-11) is not known. No equipment problem was detected. The drill rod to which the testing apparatus was attached had not slipped and packer-inflation pressure was normal.

Table 11
Summary of Injection Testing at R-22

Screen #	**2**	**3**	**4**[a]	**5**
Geologic Unit[b]	Tb	Tpt	Tbo	Tfo
Screened Interval (ft)[c]	947–988.9	1272.2–1278.9	1378.2–1384.9	1447.3–1452.3
Screen Length (ft)	41.9	6.7	6.7	5.0
Saturated Thickness (ft)	69.5	49.4	49.0	43.0
Test Design				
Pre-Test Water Level (ft)[d]	899.6	948.0	955.5	955.5
Average Injection Rate (gpm)[e]	9.12	12.0	a) 16 b) 16	17
Injection-Rate Variation (%)	<10	<10	<10	<10
Injection Period (min)	19	10	a) 3 b) 3	3
Volume Injected (gal.)	173	120	a) 48 b) 48	51
Conducted by[f]	WS	WS	WS	WS
Date	11/15/00	11/16/00	11/17/00	11/17/00
Comments:	—	Drill rod slipped 4.8 in. during test and stripped transducer cable	Two tests run with identical parameters	—
Test Results				
Analyzed by[f]	SM	SM	SM	SM
Analytical Method	Bouwer-Rice C-B-P Hvorslev	Bouwer-Rice C-B-P Hvorslev	Bouwer-Rice C-B-P Hvorslev	Bouwer-Rice C-B-P Hvorslev
Hydraulic Conductivity (ft/d)[g]	0.04 0.06 0.05	0.21 0.53 0.25	a) 0.54 0.66 0.61 b) 0.72 0.66 0.76	0.27 0.64 0.39
Comments:	Tests fairly long for slug method			

[a] Two tests were conducted for this screen to check reproducibility of results.
[b] Tb = Cerros del Rio basalt; Tpt = Puye Formation, Totavi Lentil; Tbo = older basalt; Tfo = older fanglomerate.
[c] For open interval, not screen joints.
[d] Depth bgs for packed-off interval, not well (composite static water-level depth for well = 890 ft).
[e] Determined by flowmeter and watch with second hand.
[f] WS = W. Stone, SM = S. McLin.
[g] Results are for Bouwer-Rice, C-B-P, and Hvorslev, respectively.

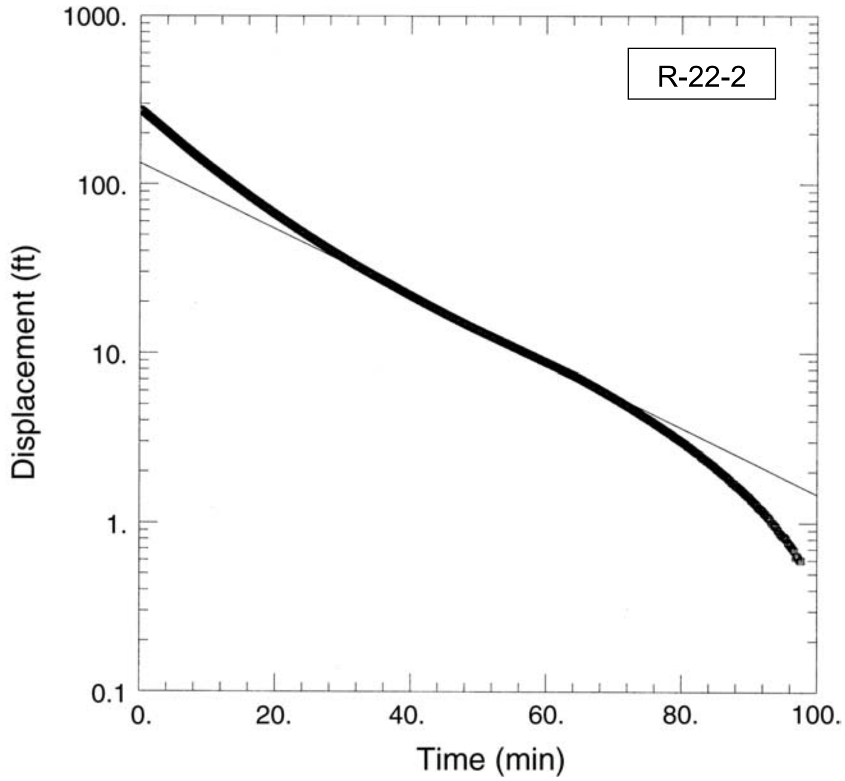

Figure 17. Bouwer-Rice analysis of injection-test recovery data for R-22, screen 2

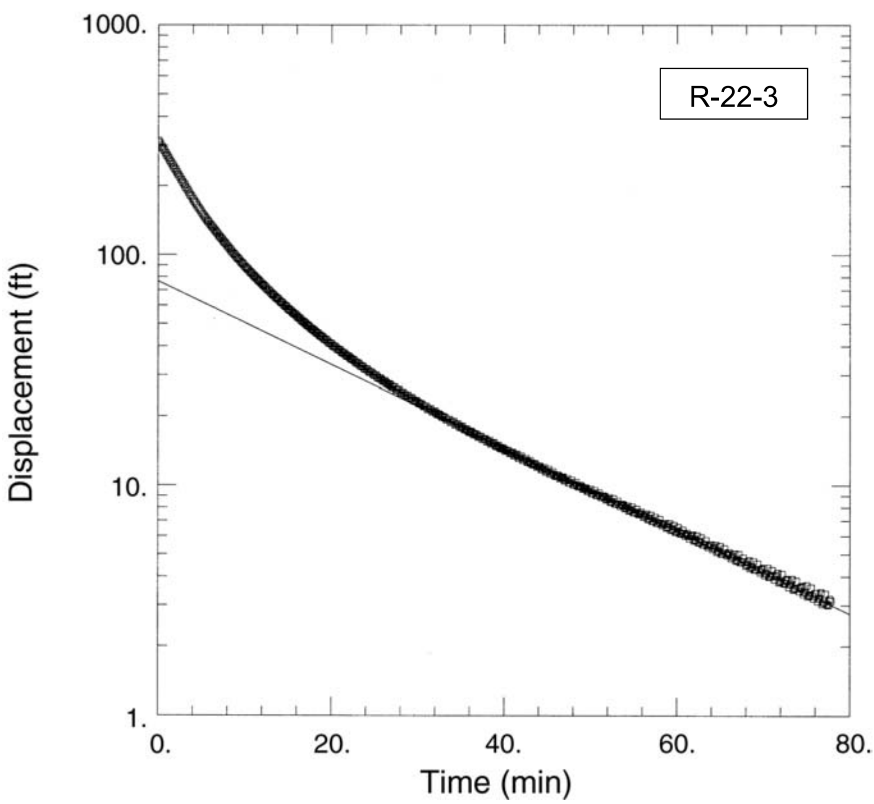

Figure 18. Bouwer-Rice analysis of injection-test recovery data for R-22, screen 3

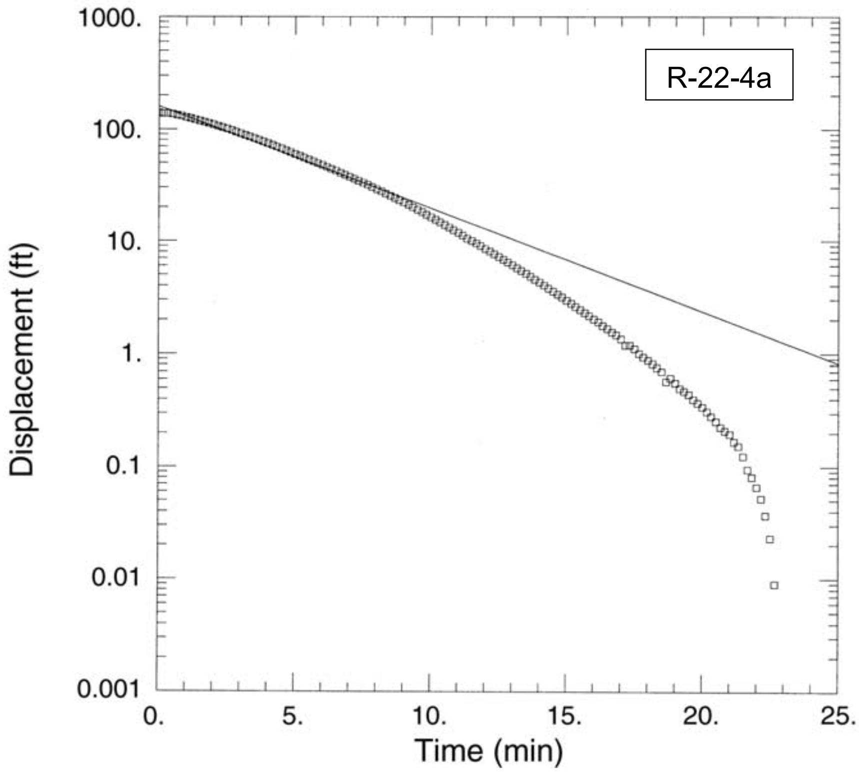

Figure 19. Bouwer-Rice analysis of injection-test recovery data for R-22, screen 4a

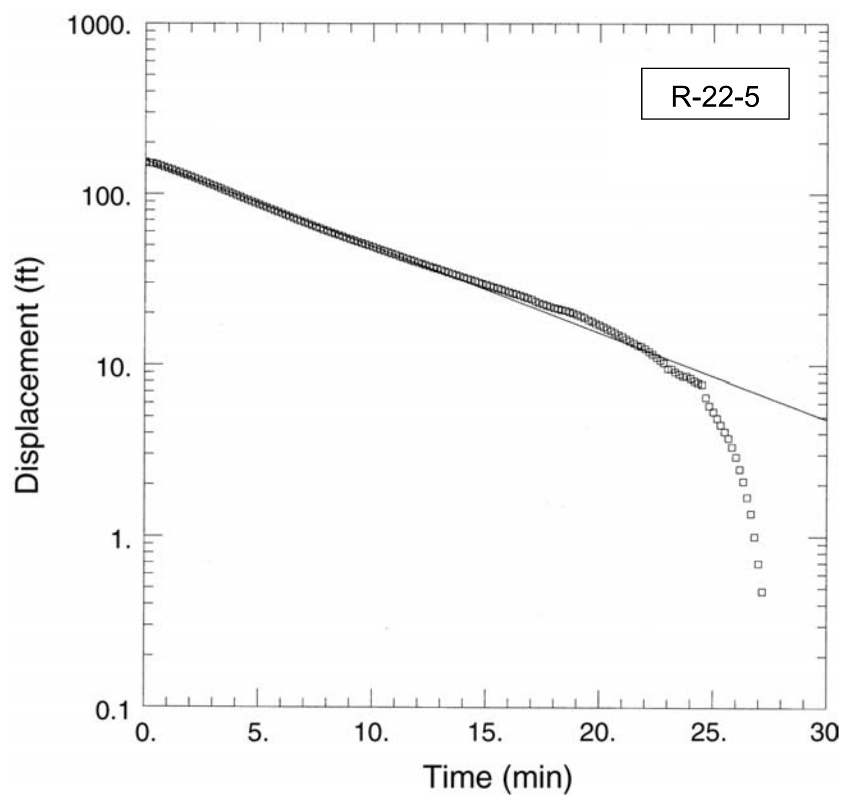

Figure 20. Bouwer-Rice analysis of injection-test recovery data for R-22, screen 5

Analysis. Plots for Bouwer-Rice analyses of data for screens 2 and 3 are concave upward as is typical for the method. However, plots for screens 4 and 5 are convex upward. After a linear segment the plot turns sharply downward. This behavior often indicates that the pre-test water level was slightly higher than the static position. A difference of only a few hundredths of a foot can cause such a response. Graphs in Appendices D-8 and D-11 confirm this condition.

Analysis of data from the injection test at screen 2 by all three methods gave similar results (Table 11). Bouwer-Rice analysis yielded a K of 0.04 ft/d. Analysis by the C-B-P method gave 0.06 ft/d (with S = 5 x 10^{-5}). Hvorslev analysis gave 0.05 ft/d.

Results of analyses of data from the injection test at screen 3 were less comparable. That is, Bouwer-Rice and Hvorslev results agree (K = 0.21 and 0.0.25 ft/d, respectively) whereas C-B-P analysis (with S = 1 x 10^{-4}) gave a K of 0.53 ft/d.

Results of analysis of data from the injection test and repeat test at screen 4 differ slightly but are of the same order of magnitude. Bouwer-Rice analysis yielded a K of 0.54 ft/d in the initial test and 0.72 ft/d in the repeat test. C-B-P analysis (with S = 1 x 10-4) gave a K of 0.66 ft/d in the initial test and 0.66 ft/d in the repeat test. Hvorslev analysis yielded a K of 0.61 ft/d for the initial test and a K of 0.76 ft/d for the repeat test.

K values obtained by the three methods for the injection-test of screen 5 are also similar. The Bouwer-Rice method gave a K of 0.27 ft/d, the C-B-P method gave 0.64 ft/d, and the Hvorslev method gave 0.39 ft/d.

WELL R-31

Well R-31 is located in TA-39 in lower Ancho Canyon (Figure 1). It was drilled by the air-rotary casing-advance method (Table 1) to a TD of 1103 ft in the Totavi Lentil (Vaniman et al. 2001, 72615). The well was completed with five screens: one in a possible perched zone of saturation, one across the water table, and three in the regional zone of saturation (Figure 21).

Hydrogeology

Geologic units penetrated by R-31 are shown in Figure 21. A possible zone of perched water was encountered in the Cerros del Rio basalt at a depth of 440 ft. The regional water table was encountered at a depth of 523 ft, also in the Cerros del Rio basalt. Preliminary head measurements from transducers in the Westbay™ monitoring system suggest either that the different screened intervals were not isolated or that well R-31 was drilled more or less parallel to an isopotential. In the latter case, groundwater flow at this location may be neither up nor down but horizontal.

Injection Tests

Soon after straddle-packer/injection testing had begun, we learned that the well (1) had not been developed according to guidance in the Field Implementation Plan and (2) was therefore only partially developed. Thus, two separate rounds of testing were performed. After three phases of additional development over 9 days, a second round of injection testing focused on screens 3 and 4. We then compared results of the initial tests with those obtained after final well development. Screen 5 was not retested because of time constraints, so the result obtained is for the first round of testing in a partially developed well. Test design and results are summarized in Table 12. Analyses of injection-test data are shown in Figures 22 through 24. Field and analytical data are given in Appendix E.

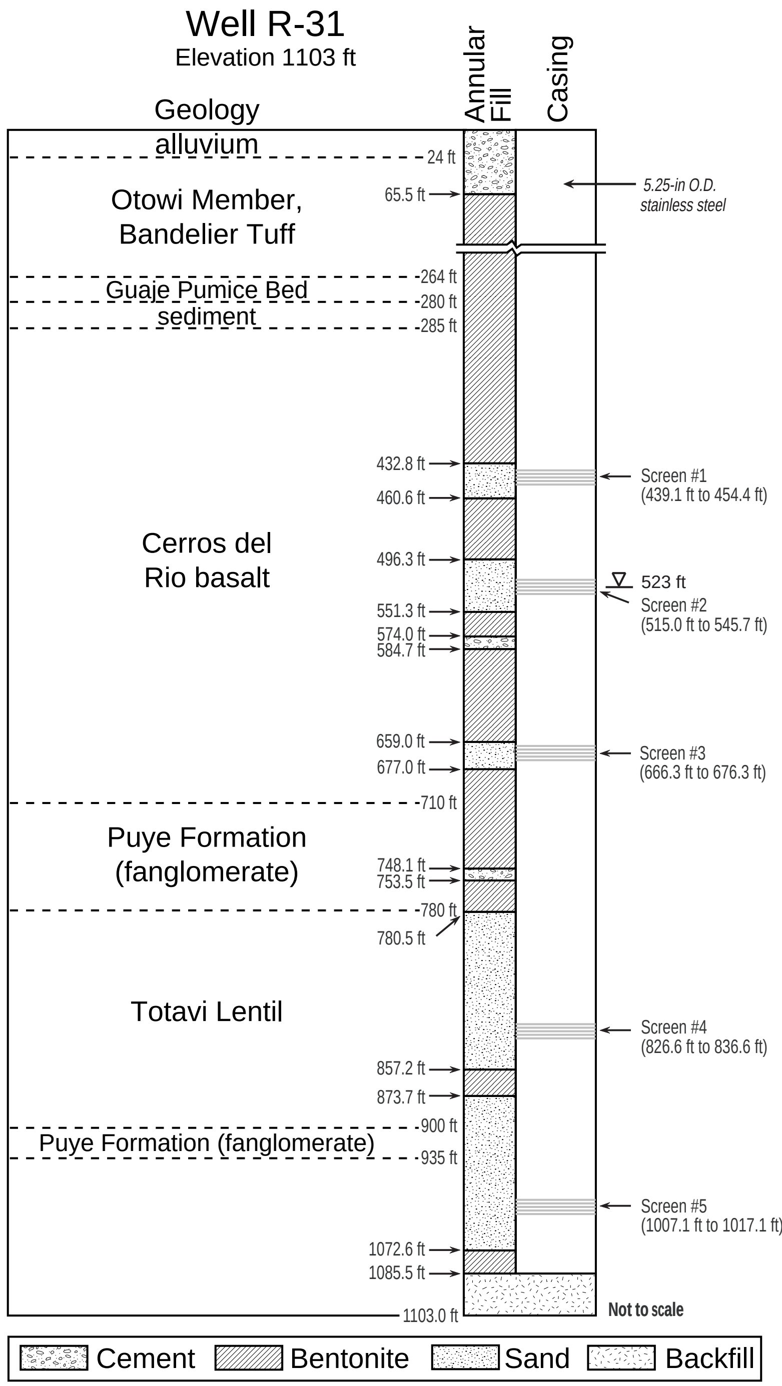

Figure 21. Hydrogeology and construction of R-31

Table 12
Summary of Injection Testing at R-31

Screen #	**3**	**4**	**5**
Geologic Unit[a]	Tb	Tpt	Tpt
Screened Interval (ft)[b]	666.3–676.3	826.6–836.6	1007.1–1017.1
Screen length (ft)[b]	10.0	10.0	10.0
Saturated Thickness (ft)	18.0	77.2	198.9
Test Design			
Pre-Test Water Level (ft)[c]	522.9	520.65	524.0
Average Injection Rate (gpm)[d]	10.9	9.8	9.0
Injection-Rate Variation (%)	<10	<10	<10
Injection Period (min)	0.92	30.5	32
Volume Injected (gal.)	10	300	270
Conducted by[e]	SM/WS	SM/WS	SM/WS
Date	3/28/00	3/28/00	3/10/00
Comments:	Two tests conducted after second round of well development; injection in second test exceeded depth capacity of transducer so not reported	Test conducted after second round of well development	Test conducted after only initial (incomplete) well development
Test Results			
Analyzed by[e]	SM	SM	SM
Analytical Method	Bouwer-Rice C-B-P Hvorslev	Bouwer-Rice C-B-P Hvorslev	Bouwer-Rice C-B-P Hvorslev
Hydraulic Conductivity (ft/d)[f]	0.41 0.48 0.53	1.23 1.40 1.48	0.75 1.35 0.88
Comments:	Analytical plots reasonable		

[a] Tb = Cerros del Rio basalt;Tpt = Puye Formation, Totavi Lentil.
[b] Length of open interval, not screen joints.
[c] Depth bgs for packed-off interval, not well (composite static water-level depth for well = 522.8 ft).
[d] Determined by flowmeter and stopwatch or watch with second hand.
[e] SM = S. McLin, WS = W. Stone.
[f] Results are for Bouwer-Rice, C-B-P, Hvorslev, respectively.

Discussion

Tests. Comparison of results from two rounds of testing conducted at R-31 (one before and one after complete well development) provided an opportunity to evaluate the impact of development on hydraulic properties obtained in testing. The second round of testing, after full development gave different values for hydraulic properties. K for material behind screen 3 decreased from 1.95 ft/d to 0.41 ft/d and K for material behind screen 4 increased from 1.09 ft/d to 1.23 ft/d with further development.

Analysis. The Bouwer-Rice plot for the screen 3 test is linear over nearly the entire test period (Figure 22). Analysis of data from the injection test at screen 3 by all three methods gave similar results. Bouwer-Rice analysis yielded a K of 0.41 ft/d, the C-B-P method gave a K of 0.48 ft/d, and Hvorslev analysis gave 0.53 ft/d.

The Bouwer-Rice plot for the test at screen 4 is concave upward, which is more typical (Figure 23). As in the case of screen 3, results by various methods for screen 4 are comparable. Bouwer-Rice analysis gave a K of 1.23 ft/d, C-B-P analysis (with $S = 5 \times 10^{-5}$) gave 1.40 ft/d, and Hvorslev analysis gave 1.48 ft/d.

The Bouwer-Rice plot for the injection test at screen 5 is similar to that for screen 4 (Figure 24). Results of analysis of the injection test at screen 5 by three methods are similar. Bouwer-Rice analysis gave a K of 0.75 ft/d, C-B-P analysis (with $S = 2.5 \times 10^{-6}$) gave a K of 1.35 ft/d, and Hvorslev analysis yielded a K of 0.88 ft/d. The results are slightly lower than those for screen 4, completed in the same geologic unit, perhaps because screen 5 was not retested after the second round of well development.

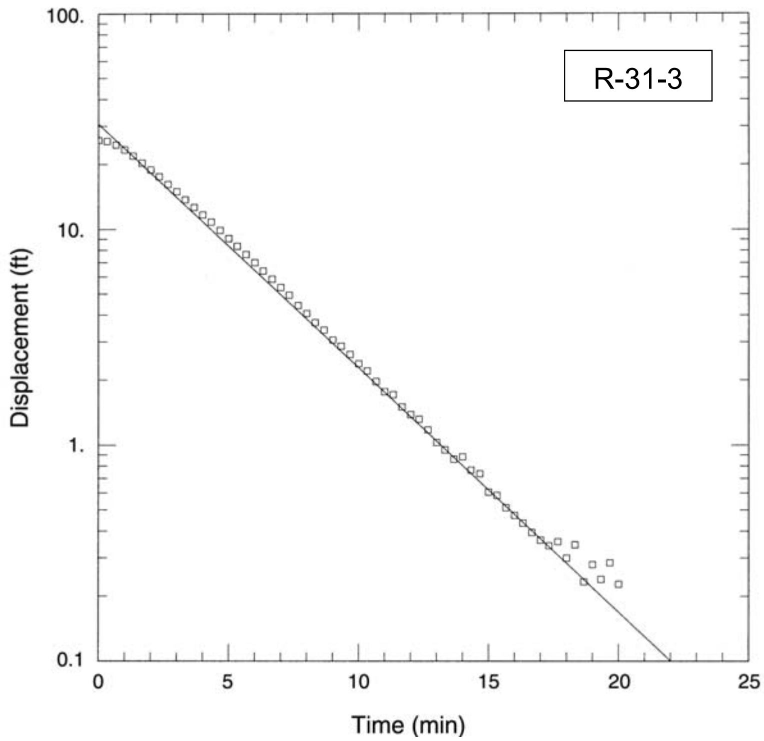

Figure 22. Bouwer-Rice analysis of injection-test recovery data for R-31, screen 3

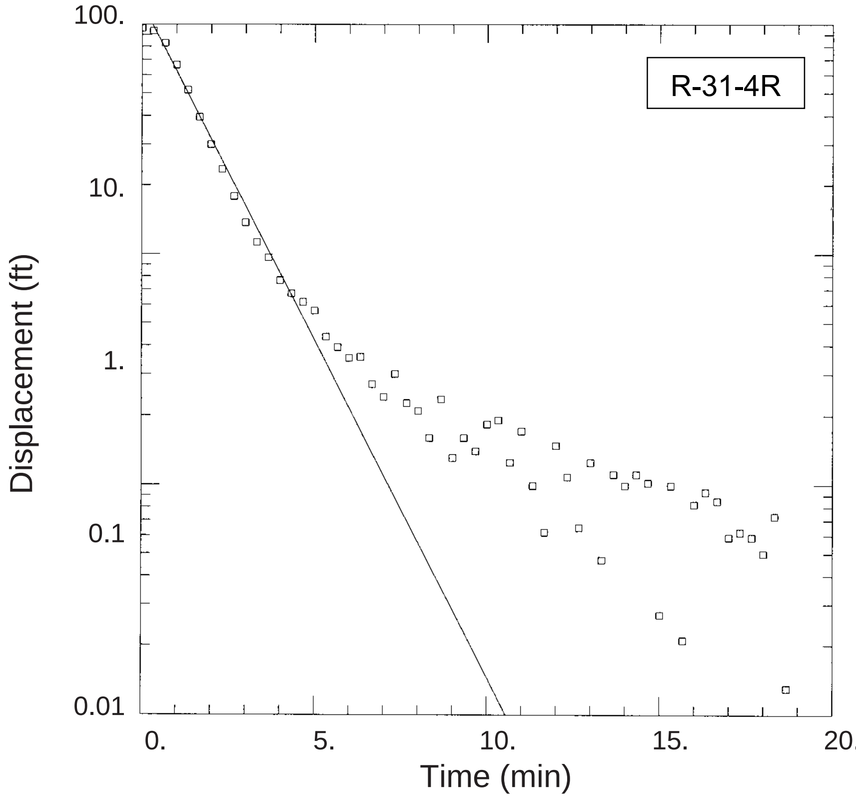

Figure 23. Bouwer-Rice analysis of injection-test recovery data for R-31, screen 4

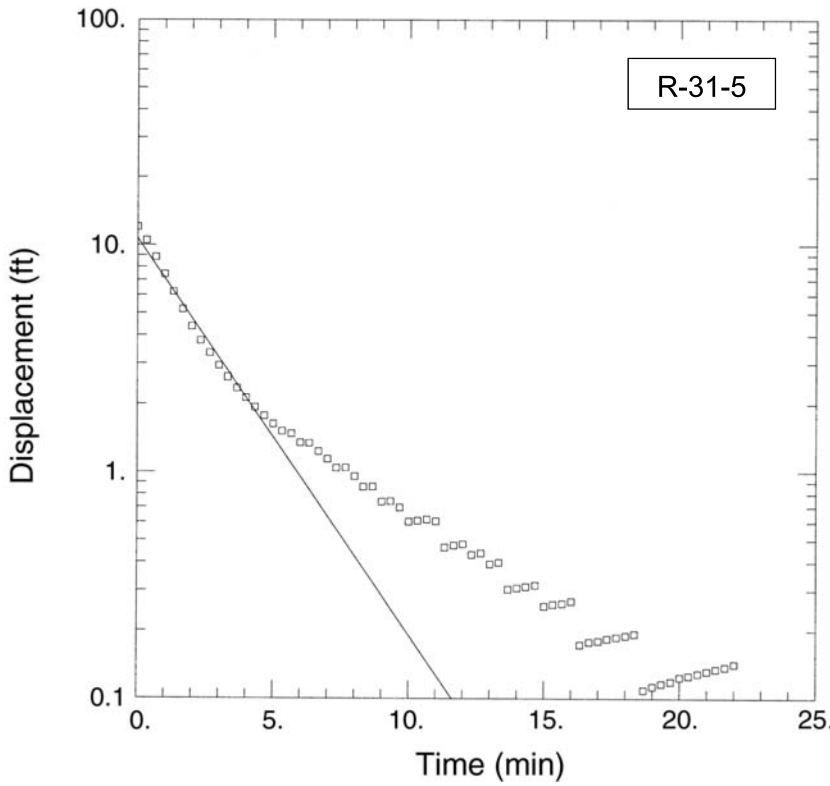

Figure 24. Bouwer-Rice analysis of injection-test recovery data for R-31, screen 5

QUALITY OF TEST RESULTS

This report not only presents the results of testing five of the R wells but also provides the details of test design, execution, and analysis necessary for users to judge the quality of test results for the R wells. Quality of test results depends on the reliability of the field data collected and validity of the analytical methods used. Addressing a few basic questions about the tests permits even further evaluation of the results.

Reliability of Test Data

The type of test conducted is an important consideration. With two exceptions (wells R-9i and R-13), testing was limited to a straddle-packer/injection method, a hybrid form of test. It is not strictly a slug test as water is not injected instantaneously. Rather, the introduction of a volume of water takes a number of minutes. Thus, the plots of water level versus time for the injection tests differ slightly from those for traditional slug tests: the slope of the initial water-level rise on the plots is not always vertical.

The reliability of hydrologic-test data depends on the uniformity of the stress applied during testing and the reliable operation of test equipment. Stress during the test, that is, the rate of water injection or withdrawal, must not vary significantly. In other words, the pump used must deliver or withdraw water at a fairly constant rate. In multi-screened wells, screens must be isolated by the packers during injection tests. Data reliability also depends on the correct functioning of all the equipment involved in measurements, including water-level probes, transducers, data loggers, flow meters, and packers. Overall, stress was applied uniformly and the testing equipment employed functioned reliably. Any exceptions are noted in the summary tables and discussion sections for the tests described herein.

Validity of Analytical Methods

Hydraulic properties are derived by analysis of test data using any of various established methods. These methods vary with hydrologic condition or aquifer type: unconfined, leaky confined, and confined. Software permits plotting data against type curves for the various methods. The type curve yielding the best fit presumably identifies the hydrologic condition prevailing for the material tested and gives the most representative result. However, the results should not be accepted uncritically but should be evaluated in view of what is known of the hydrogeology of the area.

As many analytical methods are graphical (they involve curve matching), there will always be some variation in the results. However, slight differences in curve matching yield only slight differences in results.

More important, however, is the suitability of the method used to analyze the data. Suitability is determined by the similarity of both the site and test conditions to those specified for the method. In other words, assumptions made for the method must be met. Table 13 summarizes the basic conditions assumed for the analytical methods used in this report.

Table 13
Major Assumptions for Analytical Methods Used

Method	Well Penetration of Aquifer	Hydraulic Condition	Application of Stress
Slug Tests			
Bouwer-Rice (1976, 64056)	Partial or complete	Unconfined or confined	Addition or withdrawal
Cooper-Bredehoeft-Papadopulos (1967, 70108)	Complete	Confined	Addition or withdrawal
Hvorslev (1951, 70101)	Partial	Unconfined or confined	Addition or withdrawal
Pumping Tests			
Theis (1935, 70102)	Complete	Unconfined or confined	Pumping & recovery
Hantush-Jacob (1954, 70115)	Complete	Leaky confined	Pumping & recovery
Neuman (1975, 73479)	Partial or complete	Unconfined	Pumping & recovery

Evaluating Test Results

It is beyond the scope of this report to review the field of well hydraulics. Excellent coverage can be found in standard hydrology textbooks (for example, Driscoll 1986, 70108, and Fetter 1994, 70942). However, for a quick quality-assurance check of hydrologic tests, one can ask a few basic questions:

1. *How much did flow rate vary during the test?* All analytical methods assume it was constant. However, maintaining a constant flow rate is difficult. For the test to be valid, flow rate should not have varied by more than 10%; less variation is desirable (Fetter 1994, 70942). The Bean pumps used provided remarkably constant flow rates. In all the tests reported on here, flow-rate variation was much less than 10% (typically 2-4%).
2. *Are there indications that any equipment was unreliable?* Did drill rod slip, packers deflate, the flow meter behave erratically, etc.? Obviously, unreliable equipment produces unreliable data. Whenever equipment problems occurred, testing was halted until they could be resolved.
3. *Did testing evaluate the formation or the filter pack?* Since the filter packs in some wells are long (Table 3) and the tests are short, this question seems reasonable. However, as the filter packs

are saturated when testing begins, it is not. The injection of *any* amount of water causes an equal amount of water to be displaced from the filter pack into the adjacent formation. If 5 gal. are injected, 5 gal. enter the formation, even if the pore volume of the filter pack is 25 gal. The greater the volume of water injected, the greater the volume of water going into the formation, but the formation is evaluated in all cases.

Nonetheless, comparing the volume of water injected to the pore volume of the filter pack may be of interest to some readers. To evaluate this amount, we first estimated the total volumes of the filter packs, assuming ideal cylinders (Table 14). Next, we compared the volumes of water injected with estimated pore volumes of the filter packs behind the various screens tested (Table 15). In all cases, more water was injected during testing than was needed to displace all the water in the pores of the filter pack (assuming 25% porosity). In fact, in the 11 injection tests documented in this report, injected water represented at least four times the estimated filter-pack pore volume. In nine of the tests, the volume of water injected was at least ten times the estimated pore volume. In four of the tests, the volume injected was 50 times the pore volume. In one test, the water injected represented 110 times the pore volume.

Table 14
Estimated Volume of Filter Packs in Wells Tested

Well	Screen	Borehole Radius (in.)	r_b^2 (in.^{2})[a]	Height (h) (in.)	Borehole Volume (in.^{3})[b]	Borehole Volume (ft^3)	Casing Radius (r_c) (in.)	r_c^2 (in.^{2})	Production Casing Volume (in.^{3})	Production Casing Volume (ft^3)	Filter-Pack Volume (ft^3)[c]
R-9i	1	6.12	37.45	20.7	2435.70	1.41	2.5	6.25	406.44	0.24	1.17
	2	6.12	37.45	18.5	2176.83	1.26	2.5	6.25	363.25	0.21	1.05
R-13	1	6.37	40.58	87.5	11154.16	6.45	2.78	7.7284	2124.45	1.23	5.23
R-19	6	7.00	49.00	103.9	15994.16	9.26	2.5	6.25	2040.07	1.18	8.08
	7	7.00	49.00	20.2	3109.55	1.80	2.5	6.25	396.63	0.23	1.57
R-22	2	7.25	52.56	69.5	11476.53	6.64	2.5	6.25	1364.63	0.79	5.85
	3	7.25	52.56	49.5	8173.93	4.73	2.5	6.25	971.93	0.56	4.17
	4	5.25	27.56	19.5	1688.51	0.98	2.5	6.25	382.88	0.22	0.76
	5	5.25	27.56	41	3550.20	2.05	2.5	6.25	805.03	0.47	1.59
R-31	3	6.56	43.03	18	2433.49	1.41	2.6	6.76	382.27	0.22	1.19
	4	5.37	28.84	61.5	5571.52	3.22	2.6	6.76	1306.09	0.76	2.47
	5	5.37	28.84	198.9	18019.11	10.43	2.6	6.76	4224.07	2.44	7.98

[a] r_b = borehole radius.
[b] Calculations required assumption that borehole is an ideal cylinder for which volume = $\pi r^2 h$.
[c] Filter-pack volume = borehole volume – production-casing volume.

Table 15
Volume of Water Injected vs. Pore Volume of Filter Packs in Wells Tested

Well	Screen	Borehole Volume[a] (ft^3)	Casing Volume[a] (ft^3)	Filter-Pack Volume[a] (ft^3)	Pore Volume[b] (ft^3)	Volume of Water Injected (gal.)	Volume of Water Injected (ft^3)
R-9i	1	1.41	0.24	1.17	0.29	120	16.04
	2	1.26	0.21	1.05	0.26	30	4.01
R-19	6	9.26	1.18	8.08	2.02	120	16.04
	7	1.80	0.23	1.57	0.39	322	43.05
R-22	2	6.64	0.79	5.85	1.46	140	18.72
	3	4.73	0.56	4.17	1.04	140	18.72
	4	0.98	0.22	0.76	0.19	50	6.69
	5	2.05	0.47	1.59	0.40	50	6.69
R-31	3	1.41	0.22	1.19	0.30	10	1.34
	4	3.22	0.76	2.47	0.62	300	40.11
	5	10.43	2.44	7.98	2.00	270	36.10

[a] Borehole, casing and filter-pack volumes are as derived in Table 14.
[b] Pore volume based on assumption of 25% porosity; primary and secondary filter-pack sands not distinguished for this estimate.

4. *Were the assumptions for the analytical method used actually met at the site?* Unrealistic or erroneous hydraulic properties are often attributed to the inadequacy of the analytical equation used. It is more likely that any of several field conditions did not match those on which the equation is based:

   Screen Position. Tests for screens straddling the water table are not ideal, as discussed under "Constraints." Although a few methods specifically state that they apply only to tests of screens below the water table (for example, Bouwer and Rice), that assumption is inherent for all methods.

   Well Penetration of Aquifer. Ideally, a well to be tested fully penetrates the thickness of an aquifer. Some methods are suitable for partially penetrating wells, others require fully penetrating wells, and some apply to either case, especially if certain conditions are met. If a screen covers less than 70% of the total thickness of the saturated material, the well is considered to be partially penetrating (Kruseman and de Ridder 2000, 70110). The multiscreen completion of most of the wells epitomizes partial penetration. Short single-screen completions also represent only partial penetration. Well penetration is a concern in test analysis. What saturated thickness should be applied to each screen? Is it the interval between seals (filter-pack length) or that between the lower seal and the composite static water level for the entire well? For consistency, we usually defined the saturated thickness as the filter-pack length.

   Hydraulic Condition. Some methods apply only to confined conditions, others apply only to unconfined conditions, while still others apply to leaky-confined conditions. Some apply to either confined or unconfined conditions, if certain provisions apply. If an analytical plot looks good for a given condition, one should consider whether that condition is likely for the location and material behind the screen.

   Flow Conditions. Each analytical method corresponds to a specific flow condition. Flow to the well is assumed to be radial. For pumping tests, flow may also be further described as steady (in equilibrium) or nonsteady (not in equilibrium). In steady flow, the cone of depression continues to grow with time. In nonsteady flow, the cone of depression has reached a recharge boundary and stopped growing.

Method of Applying Stress. Some methods evaluate the response to removal of water (as by pumping), while others address the response to addition of water. Alternatively, the same results can be generated by introducing or removing a solid slugger of known volume to or from the water column in the well (conventional slug tests).

Major assumptions for the methods used to analyze data from the five wells tested are summarized in Table 13.

5. *Do the test results for the various geologic units compare favorably with those obtained previously?* Figure 25 permits a comparison of the results of the injection testing described herein and those obtained for the same geologic unit by various other methods. In most cases, injection-test results fall within the distribution of values. In general, however, results of injection tests tend to be lower than those of pumping tests.

6. *Do the results seem reasonable for the geologic materials tested?* That is, are the hydraulic properties within the range commonly reported for the rock types tested? Table 16 gives the lithology of the material tested, the results obtained from testing (K), and the range of textbook K values for the same or most similar material. All of the test results fall within reported ranges of K for the geologic materials tested.

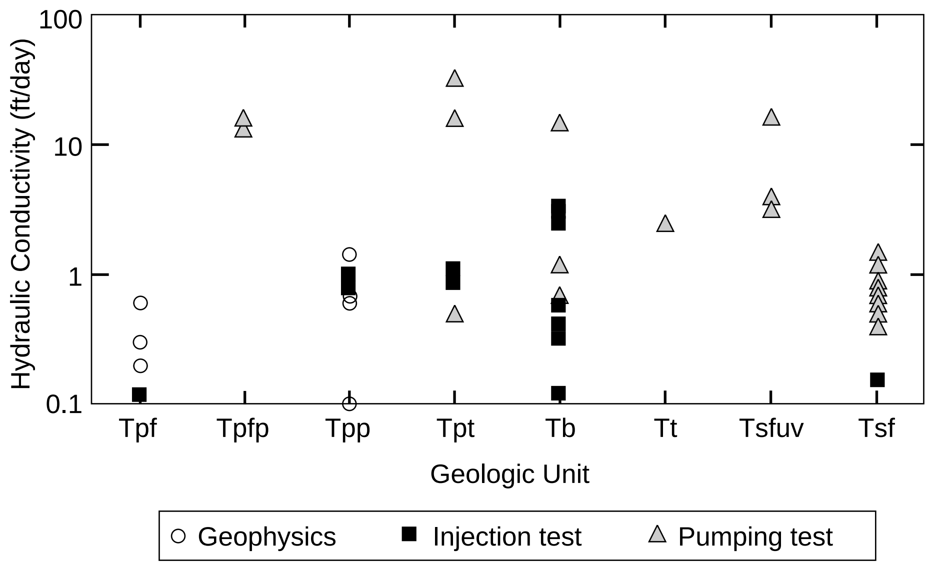

Figure 25. Comparison of results for various test methods. Tpf = Puye Formation (fanglomerate); Tpp = Puye Formation (pumiceous); Tpfp = Puye Formation (fanglomerate and pumiceous); Tpt = Puye Formation, Totavi Lentil; Tb = Cerros del Rio basalt; Tt = Tschicoma Formation; Tsfuv = upper Santa Fe Group; and Tsf = Santa Fe Group

Table 16
Hydraulic Properties vs. Geology

Material Tested (well-screen/test) [a]	Test Results K (ft/d)	(gpd/ft^2)[b]	Comparable Textbook Material[c]	Textbook K Range (gpd/ft^2)[c]
Clayey flow base (R-9i-2)	0.11	0.82	Glacial till	10^{-5} to 10
Massive/somewhat fractured basalt			Fractured igneous and metamorphic rock	$10^{-1}$to 10^{3}
(R-22-2)	0.04	0.30		
(R-31-3)	0.41	3.07		
(R-22-4a)	0.54	4.04		
(R-22-4b)	0.72	5.39		
Highly fractured basalt			Permeable basalt	1 to10^{5}
(R-9i-1a)	4.87	36.43		
(R-9i-1)*	4.75	35.53		
Fanglomerate and axial gravel			Silty sand	1 to 10^{3}
(R-22-3)	0.21	1.57		
(R-22-5)	0.27	2.02		
(R-19-7)p	0.73	5.46		
(R-31-5)g	0.75	5.61		
(R-19-6)p	1.10	8.23		
(R-31-4)g	1.23	9.20		
(R-13b)*	13.70	102.48		

[a] * = pumping test and K = T/saturated thickness; p = pumiceous fanglomerate (Puye Formation), g = gravel (Totavi Lentil).
[b] Calculated as ft/d value (Table 5) x 7.48.
[c] From Freeze and Cherry (1979, 64057) Table 2.2.

Despite the care taken in the design, execution, and analysis of tests, results obtained are not unique. Kruseman and DeRidder (2000, p. 13, 70110) summed up the reason succinctly:

> Analyzing and evaluating pumping test data…is as much an art as a science. It is science because it is based on theoretical models that the geologist or engineer must understand and on thorough investigations that he [/she] must conduct into the geologic formations in the area of interest. It is an art because different types of aquifers can exhibit similar drawdown behaviors, which demand interpretation…on the part of the geologist or engineer.

This dual nature of hydrologic testing should be kept in mind when evaluating or using test results.

RECOMMENDATIONS

As noted in the "Constraints" section, the R wells present several challenges to hydrologic testing. We offer the following suggestions for overcoming these challenges and optimizing opportunities for evaluating hydraulic properties of the saturated materials beneath the Pajarito Plateau.

Avoid Placing Screens Across Water Table. Designing wells with testing in mind maximizes both testing opportunities and results. Most analytical methods assume the screen is below the water table. NMED has specified that the uppermost screen must straddle the water table to facilitate detection of organic contaminants floating at the top of the saturated zone, despite the fact that organics are not the principal contaminants at LANL. Furthermore, such a well design hinders development of the uppermost screen. Thus, we recommend that screens not be paced across the water table, unless there is a reason to suspect organic contaminants in the area.

Avoid Placing Screens Across Geologic Contacts. Hydrologic testing is usually conducted to learn the properties of a single geologic unit or type of material within a geologic unit. When screens are placed across contacts between geologic units, the test result is an average that is not representative of either unit. Thus, we recommend that placing screens across geologic contacts or contacts between material types within units should be avoided wherever possible.

Avoid Oversized Filter Packs. Oversized filter packs should be avoided as they hinder focused hydrologic testing and water-quality sampling. One usually assumes that the interval of geologic material targeted by a screen is similar to the length of the screen. Thus, it is not only misleading but also counterproductive to have a 7-ft screen and a 100-ft filter pack (as at R-19, screen 6; Table 4). Results of testing such a screen installation are biased by the amount of permeable material in such a long interval. Furthermore, many of the R wells are destined to become monitoring wells. Such wells usually target certain intervals in the saturated zone. Oversized filter packs permit the mixing of water over long intervals. It is not possible to characterize the quality of water associated with material behind a 7-ft screen if the water sample actually came from a bracketing 100-ft interval.

Employ Alternative Test Methods. Ideally, a given saturated material would be tested by as many methods as possible and the results compared. For example, injection tests, slug tests, and pumping tests could be conducted in the same well. Testing of the multiscreened R wells has been by a straddle-packer/injection method. Slug and pumping tests between straddle packers should also be performed. However, equipment for such testing was not available for wells discussed in this report. The added expense of applying multiple methods would be minimal as equipment is already at the well site. Costs would also be minimized by employing multiple methods only until the relationship of results is determined.

Tests employing a solid slugger would not only be simpler but would have the advantage of eliminating the need to introduce foreign water. As equipment is not readily available, an assembly must be fabricated to permit such testing between straddle packers. A major design challenge, however, is accommodating a transducer and a solid slugger in the small production casing, without tangling/damaging the transducer cable or compromising the seal provided by the packer.

One possible alternative approach to traditional slug testing in the multiscreened wells would be to add a valve to the straddle-packer/injection assembly currently used that could be tripped from the surface. In this case one would add a known volume of water to the rods above the valve and then trip it for instantaneous delivery to the screened interval, as assumed in slug testing. Another alternative is to use a pulse of air as the “slug.” In these and the solid-slugger cases, analytical methods intended for slug tests would be directly applicable.

Screen-specific pumping tests, in which water is withdrawn from between a pair of packers isolating screens, would also be ideal. Such tests would provide additional hydraulic-property results for comparison with those from straddle-packer/injection or slug tests. For such tests, a pump must (1) fit inside a 4.5-in. production casing, (2) lift water against the heads involved in these deep wells, and (3) discharge at a rate great enough to stress the saturated zones. However, we have not succeeded in obtaining a pump that will do all three. Where hydrologic data are an objective, larger diameter wells should be installed.

Hydraulic properties can also be evaluated by means of water-level time-series analysis, especially with respect to the response to atmospheric pressure and earth tides (Ritzi et al. 1991, 73645; McLin 2000, 73735). The water levels collected to date by LANL’s transducer network are a valuable source of data for such analysis. Results would complement and provide a further check of field-test results.

Employ Alternative Test Designs. The results reported here are all based on single-well tests. It could be argued that such tests interrogate only a small portion of the saturated material next to the well and that material may have been damaged during drilling and well construction. Multiwell tests, involving a pumping well and one or more observation wells, cover a larger portion of the saturated medium (that between the pumping and observation wells) and thus give more representative results (Kruseman and de Ridder 2000, 70110). Such tests also permit the calculation of storativity and anisotropy. The Hydrogeologic Workplan (LANL 1998, 59599) recognizes the need for multiwell tests, and it is hoped that some will be conducted before the program is concluded.

Pumping tests should involve as many observation wells (piezometers) as possible. Kruseman and de Ridder (2000, 70110) recommend employing at least three. Spacing and orientation depend on site conditions. Placing piezometers 30 to 300 ft from the pumping well is sufficient in most cases; however, a spacing on the order of 300 to 800 ft may be required for thick or stratified, confined aquifers. A well or piezometer located outside the radius of influence of the pumping well is also useful. Any water-level changes related to natural recharge or discharge detected in such a well can be used to correct drawdowns induced by pumping.

If funding permits only two-well tests, they could be most economically accomplished by locating selected R wells near existing water-supply wells. In such an arrangement, the supply well could be the pumping well and the R well could be the observation well. The use of a municipal well solves the problem of disposal of produced water: it would go into the supply line. However, the construction of supply wells is not always ideal for hydrologic testing. That is, screens may be long and extend over multiple hydrostratigraphic units.

If no supply well exists where a test is needed or if the construction of existing supply wells is not appropriate, an R well can be installed to be either the pumping well or an observation well. If the R well is completed with a single screen and used as the pumping well, the observation well(s) can be a small-diameter piezometer(s). The piezometer(s) must be constructed so as to be compatible with the pumping well (same unit screened, etc.) or with the test objective.

Repeat Tests When Practical. Conducting more than one test using the same method on the same screen and comparing results is instructive and should be done where feasible. Some repeat tests were made for the wells reported here but not consistently. Retesting should become routine practice, at least until it is shown that results are reproducible. In the case of injection or pumping tests, a second test can be run after water level has returned to the pre-test static position. In the second round of testing, flow rate and duration can be kept the same or changed. The additional expense amounts to a few hours of rig, crew, and LANL-staff time, which is small when compared to the total cost of a well.

Verify Development With Testing. Hydrologic testing assumes the well has been completely developed. Even if field parameters reach acceptable levels, the two-layer screen (as currently in use), the filter pack or the adjacent formation may not be completely open. A series of tests can be performed to verify that well development has completely removed all drilling fluids or that borehole skin effects do not dominate the flow regime (Butler 1997, 73641). Ideally, at least three tests are employed sequentially: slug withdrawal first, then slug injection, and finally slug withdrawal. The resulting impact on the well is much like surging during well development. Generally, during the final test, the maximum slug-injection head is about twice the initial slug-injection head. This series gives results for flow both into and out of the formation. If these tests replicate one another, then one has high confidence that well development was adequate, and that the reported hydraulic conductivity values represent the undisturbed formation surrounding the well screen.

Even if the exact series of tests described above cannot be performed, repeat tests can tell something about development. For example, if the recovery curve for the initial falling-head test is rough but that for subsequent tests is smooth, one may conclude that the initial injection accomplished some development.

Target Selected Hydrostratigraphic Units. Figure 25 shows that the injection tests reported here have not included the deeper geologic units (Tt, Tsfuv, and Tsf). This can be explained by the fact that the R wells do not usually penetrate these units. Results of recent numerical modeling of the groundwater system beneath the Pajarito Plateau suggest that existing data adequately characterize the hydraulic properties for the Santa Fe Group. Thus, future testing in the deep wells should focus on other units for which aquifer properties are poorly constrained, namely, the Cerros del Rio basalt and the Puye Formation. Hydraulic conductivity data obtained from testing to date vary considerably for both of these units (Stone et al. 2001, 70090).

Testing every screen in every well may not be necessary or economical. As noted above, testing screens straddling the water table is not appropriate. Additionally, if a given unit has been fairly well characterized by previous testing or if several screens are set in the same unit in the well, testing may be limited to selected screens.

SUMMARY AND CONCLUSIONS

The key findings of the tests and conclusions based on them are summarized below.

1. Eleven straddle-packer/injection tests and two pumping tests have been conducted at five wells: R-9i, R-13, R-19, R-22, R-31.
2. Although testing by injection between straddle packers is a hybrid method, it was the only one available for the deep, multiscreened wells being installed on the Pajarito Plateau.
3. Four of the eleven injection tests evaluated the Cerros del Rio basalt. K values for the basalt range from 0.04 to 4.87 ft/d. Such a range of values is expected given the variability of porosity and permeability within basalts.
4. Two of the eleven injection tests involved the Puye Formation, pumiceous unit, in the same well (R-19). Results of the tests are very similar: 0.73 and 1.10 ft/d, no doubt a result of similar depositional conditions, and thus similar porosity and permeability, for this unit of the Puye lying behind the two screens tested.
5. Two other tests involve the Totavi Lentil of the Puye Formation, in the same well (R-31). K values determined from these tests are 1.23 ft/d (screen 4) and 0.75 ft/d (screen 5).
6. The remaining three injection tests each targeted a different geologic unit. K for the Puye Formation at R-22, screen 3 = 0.21 ft/d; K for older basalt at R-22, screen 4 = 0.54 ft/d; and K for older fanglomerate at R-22, screen 5 = 0.27 ft/d.
7. Hydraulic properties at two wells were evaluated by pumping tests: R-9i and R-13. For Cerros del Rio basalt at R-9i, screen 1, T = 49.4 ft^2/d or K = 4.75 ft/d. This K is very similar to that obtained in the injection test (K = 4.87 ft/d). For the Puye Formation at R-13, T is at least 829.7 ft^2/d (K = 13.7 ft/d). As the screen straddles the contact between fanglomerate and pumiceous Puye, this is a composite value. Discharge was too low with the pump available to stress the regional aquifer at R-13 and the test was cut short.
8. In spite of constraints imposed by hydrogeology and well design, hydrologic testing yielded reasonable order-of-magnitude results when compared both with those of previous testing on the Pajarito Plateau and with values commonly reported for similar materials outside the area.
9. We recommend that screens not be placed across the water table or geologic contacts and that oversized filter packs be avoided.
10. Alternative test methods and designs should be employed and results compared, at least until relationships have been determined.
11. Development could be verified by a series of slug tests, as used elsewhere.
12. Testing should be focused on selected hydrostratigraphic units for which data are sparse.

Although major saturated materials beneath the Pajarito Plateau have been previously tested, especially in the water-supply wells, details of some such tests have not been preserved, and those for others are incomplete or not readily available. Thus, the validity of many of the previous tests cannot be determined. It is hoped that since this document not only presents results of testing at five of the new R wells but also captures and preserves information about the test design, implementation, and analysis needed to evaluate the quality of these results, it will be even more useful to readers.

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Appendix A

Well R-9i Test Data

Contents

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A-3 Analysis of Injection Test, Screen 1a

A-4 Plot for Injection Test, Screen 2

A-5 Recovery Data for Injection Test, Screen 2

A-6 Analysis of Injection Test, Screen 2

A-7 Plot for Pumping Test

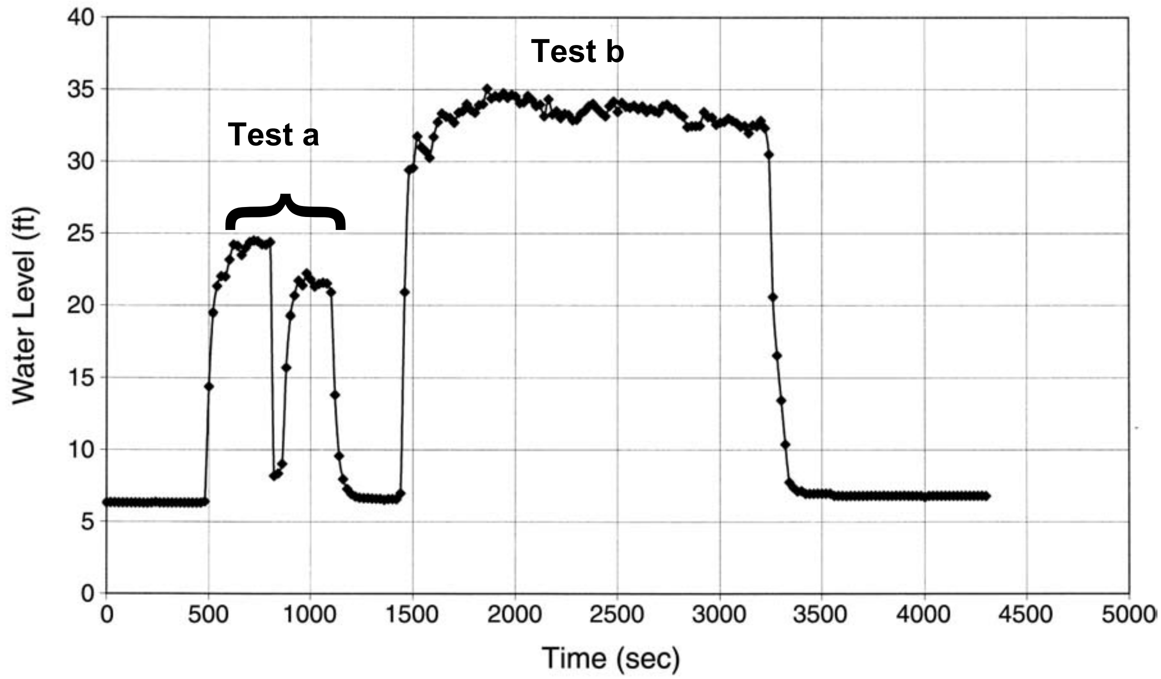
A-8 Drawdown Data for Pumping Test

A-9 Analysis of Pumping Test (Theis)

A-10 Analysis of Pumping Test (Neuman, early-time data)

A-11 Analysis of Pumping Test (Neuman, late-time data)

A-1. Plots for Injection Tests, R-9i, Screen 1



A-2. Recovery Data for Injection Test, R-9i, Screen 1a

t (sec)	s (ft)
20.00	14.32
40.00	7.23
60.00	2.99
80.00	1.38
100.00	0.69
120.00	0.34
140.00	0.16
160.00	0.09
180.00	0.06
200.00	0.06
220.00	0.04
240.00	0.02

A-3. Analysis of Injection Test, R-9i, Screen 1a

Test Date: 10 Apr 00

Aquifer Data

Saturated thickness:	61.9 ft
Anisotropy ratio (Kz/Kr):	1

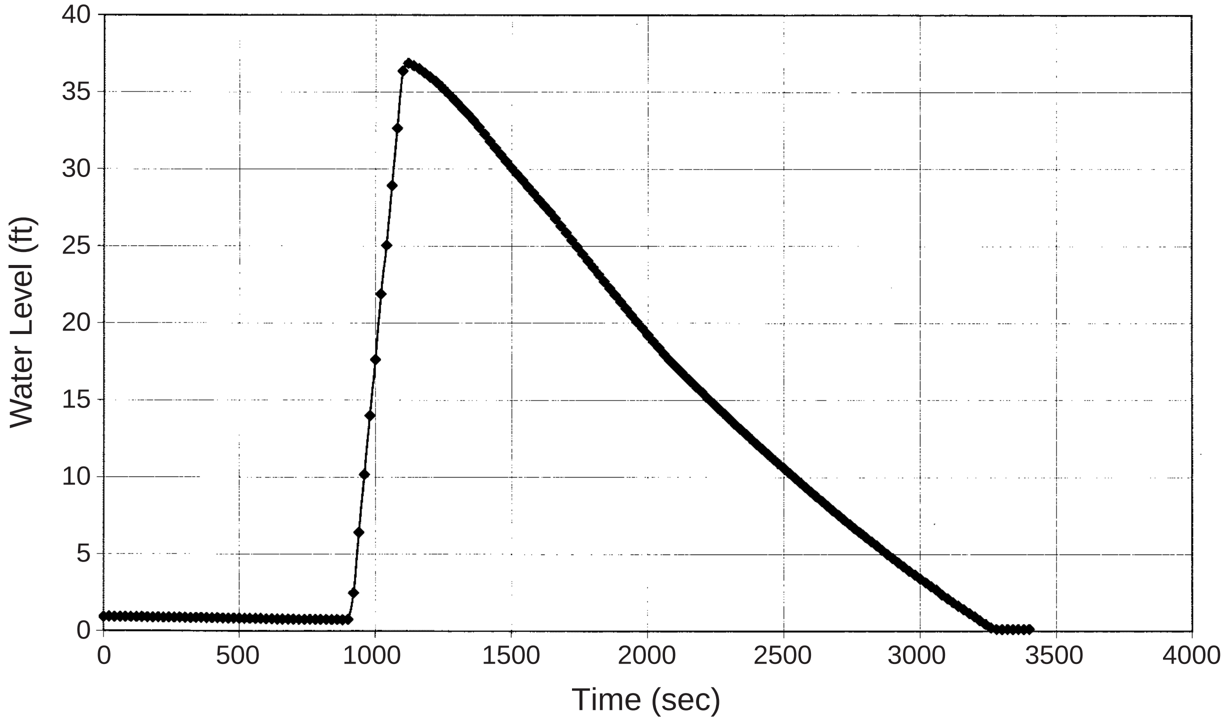
Well Data

Initial displacement:	14.9 ft
Depth of penetration:	61.9 ft
Casing radius:	0.0990 ft
Borehole radius:	0.5104 ft
Screen length:	10.4 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	unconfined
K =	4.87 ft/d
y_0 =	30.36 ft

A-4. Plot for Injection Test, R-9i, Screen 2



A-5. Recovery Data for Injection Test, R-9i, Screen 2

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
0.33	144.13	6.33	118.61	12.33	87.50	18.33	58.67
0.67	143.53	6.67	116.95	12.67	85.69	18.67	57.29
1.00	142.73	7.00	115.28	13.00	83.95	19.00	55.92
1.33	141.65	7.33	113.70	13.33	82.20	19.33	54.54
1.67	140.55	7.67	112.06	13.67	80.48	19.67	53.18
2.00	139.46	8.00	110.38	14.00	78.74	20.00	51.83
2.33	138.21	8.33	108.64	14.33	77.02	20.33	50.50
2.67	136.76	8.67	107.09	14.67	75.27	20.67	49.18
3.00	135.34	9.00	105.57	15.00	73.59	21.00	47.93
3.33	133.81	9.33	103.81	15.33	71.91	21.33	46.61
3.67	132.29	9.67	101.94	15.67	70.29	21.67	45.32
4.00	130.78	10.00	100.10	16.00	68.65	22.00	44.06
4.33	129.22	10.33	98.26	16.33	67.09	22.33	42.80
4.67	127.59	10.67	96.43	16.67	65.64	22.67	41.45
5.00	125.70	11.00	94.62	17.00	64.22	23.00	40.25
5.33	123.87	11.33	92.82	17.33	62.80	23.33	39.01
5.67	122.10	11.67	91.06	17.67	61.45	23.67	37.78
6.00	120.37	12.00	89.28	18.00	60.03	24.00	36.52

t (min)	s (ft)
24.33	35.30
24.67	34.07
25.00	32.83
25.33	31.63
25.67	30.41
26.00	29.22
26.33	28.05
26.67	26.83
27.00	25.66

t (min)	s (ft)
27.33	24.48
27.67	23.36
28.00	22.26
28.33	21.13
28.67	20.01
29.00	18.91
29.33	17.82
29.67	16.66

t (min)	s (ft)
30.00	15.58
30.33	14.49
30.67	13.42
31.00	12.34
31.33	11.33
31.67	10.33
32.00	9.31
32.33	8.29

t (min)	s (ft)
32.67	7.43
33.00	6.17
33.33	5.18
33.67	4.18
34.00	3.22
34.33	2.25
34.67	1.30
35.00	0.40

A-6. Analysis of Injection Test, R-9i, Screen 2

Test Date: 10 Apr 00

Aquifer Data

Saturated thickness:	18.8 ft
Anisotropy ratio (Kz/Kr):	1

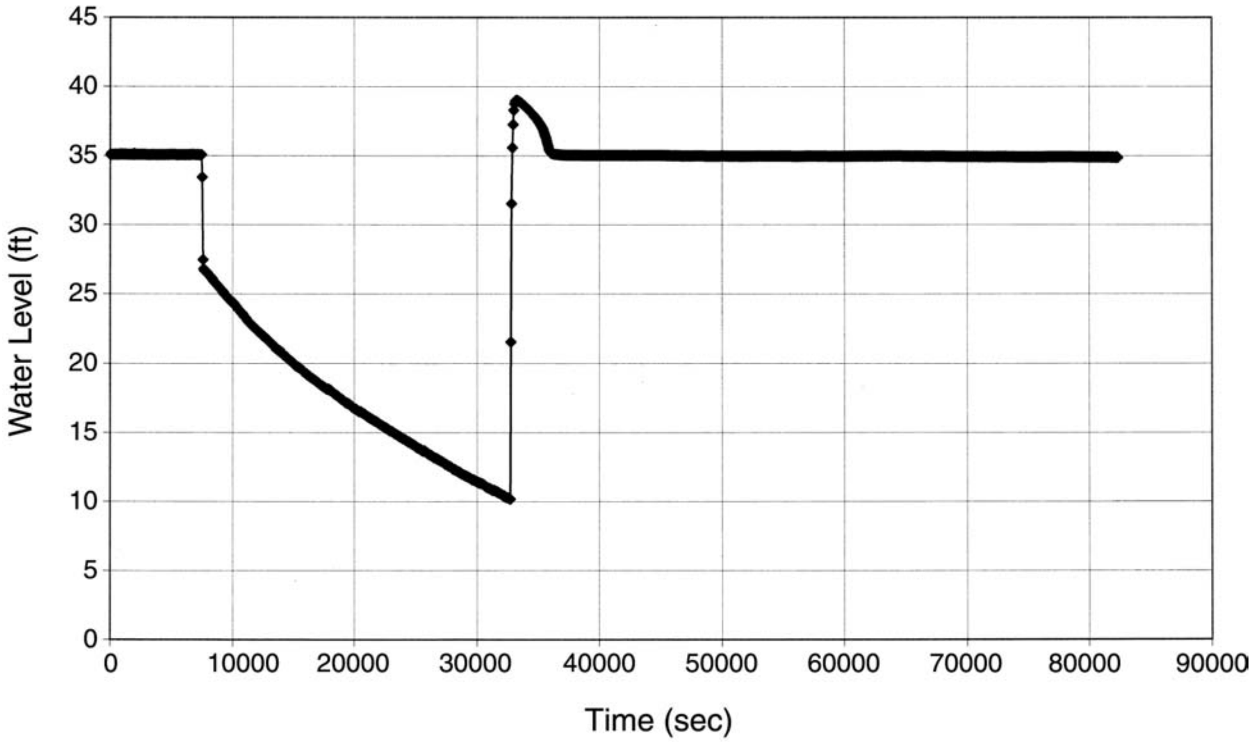
Well Data

Initial displacement:	145 ft
Depth of penetration:	18.8 ft
Casing radius:	0.0990 ft
Borehole radius:	0.5104 ft
Screen length:	10.7 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	unconfined
K =	0.11 ft/d
y_0 =	167.9 ft

A-7. Plot for Pumping Test, R-9i



A-8. Drawdown Data for Pumping Test, R-9i

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
3	8.27	20	9.36	37	10.44	54	11.41
4	8.39	21	9.42	38	10.49	55	11.50
5	8.42	22	9.49	39	10.55	56	11.51
6	8.43	23	9.53	40	10.62	57	11.57
7	8.49	24	9.59	41	10.68	58	11.70
8	8.54	25	9.68	42	10.65	59	11.75
9	8.66	26	9.73	43	10.68	60	11.80
10	8.69	27	9.79	44	10.75	61	11.85
11	8.76	28	9.82	45	10.87	62	11.95
12	8.82	29	9.95	46	10.89	63	12.04
13	8.90	30	9.95	47	10.97	64	12.08
14	8.93	31	10.09	48	11.02	65	12.17
15	9.02	32	10.14	49	11.10	66	12.20
16	9.12	33	10.18	50	11.21	67	12.26
17	9.19	34	10.24	51	11.22	68	12.28
18	9.25	35	10.34	52	11.28	69	12.37
19	9.30	36	10.39	53	11.35	70	12.44

t (min)	s (ft)
71	12.44
72	12.50
73	12.53
74	12.61
75	12.66
76	12.73
77	12.76
78	12.83
79	12.87
80	12.90
81	12.96
82	12.99
83	13.04
84	13.13
85	13.14
86	13.22
87	13.23
88	13.29
89	13.32
90	13.37
91	13.44
92	13.49
93	13.52
94	13.62
95	13.63
96	13.72
97	13.75
98	13.83
99	13.85
100	13.87
101	13.95
102	14.02
103	14.03
104	14.09
105	14.13
106	14.18
107	14.20
108	14.23
109	14.30
110	14.32
111	14.39

t (min)	s (ft)
n112	14.45
113	14.49
114	14.52
115	14.58
116	14.59
117	14.66
118	14.69
119	14.75
120	14.81
121	14.83
122	14.89
123	14.92
124	14.98
125	15.01
126	15.06
127	15.14
128	15.15
129	15.24
130	15.28
131	15.29
132	15.32
133	15.36
134	15.38
135	15.41
136	15.46
137	15.51
138	15.55
139	15.62
140	15.68
141	15.74
142	15.77
143	15.79
144	15.82
145	15.91
146	15.92
147	15.95
148	16.02
149	16.05
150	16.10
151	16.12
152	16.17

t (min)	s (ft)
153	16.20
154	16.24
155	16.28
156	16.32
157	16.35
158	16.40
159	16.44
160	16.48
161	16.53
162	16.58
163	16.61
164	16.65
165	16.70
166	16.73
167	16.77
168	16.80
169	16.81
170	16.87
171	16.91
172	16.95
173	16.94
174	16.93
175	16.95
176	17.03
177	17.03
178	17.07
179	17.13
180	17.18
181	17.23
182	17.28
183	17.31
184	17.34
185	17.38
186	17.41
187	17.46
188	17.50
189	17.56
190	17.59
191	17.64
192	17.69
193	17.70

t (min)	s (ft)
194	17.74
195	17.79
196	17.86
197	17.89
198	17.94
199	17.93
200	17.94
201	18.00
202	18.03
203	18.04
204	18.10
205	18.13
206	18.22
207	18.24
208	18.30
209	18.33
210	18.34
211	18.39
212	18.40
213	18.46
214	18.49
215	18.53
216	18.57
217	18.57
218	18.56
219	18.62
220	18.65
221	18.69
222	18.72
223	18.73
224	18.77
225	18.82
226	18.87
227	18.92
228	18.95
229	18.97
230	19.02
231	19.03
232	19.07
233	19.09
234	19.15

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
235	19.18	276	20.55	317	21.88	358	23.16
236	19.20	277	20.56	318	21.90	359	23.19
237	19.26	278	20.59	319	21.93	360	23.21
238	19.26	279	20.62	320	21.93	361	23.23
239	19.28	280	20.67	321	21.97	362	23.26
240	19.33	281	20.71	322	22.01	363	23.29
241	19.35	282	20.74	323	22.01	364	23.30
242	19.39	283	20.78	324	22.05	365	23.34
243	19.45	284	20.77	325	22.08	366	23.37
244	19.48	285	20.81	326	22.13	367	23.42
245	19.52	286	20.87	327	22.14	368	23.44
246	19.55	287	20.89	328	22.18	369	23.49
247	19.59	288	20.91	329	22.21	370	23.50
248	19.61	289	20.95	330	22.24	371	23.52
249	19.65	290	20.98	331	22.30	372	23.52
250	19.68	291	21.04	332	22.31	373	23.57
251	19.71	292	21.05	333	22.37	374	23.59
252	19.78	293	21.09	334	22.38	375	23.63
253	19.75	294	21.17	335	22.43	376	23.66
254	19.82	295	21.20	336	22.46	377	23.67
255	19.85	296	21.20	337	22.51	378	23.70
256	19.88	297	21.24	338	22.51	379	23.72
257	19.93	298	21.27	339	22.54	380	23.76
258	19.96	299	21.31	340	22.57	381	23.76
259	19.98	300	21.31	341	22.60	382	23.76
260	19.99	301	21.37	342	22.64	383	23.80
261	20.03	302	21.42	343	22.73	384	23.82
262	20.06	303	21.42	344	22.74	385	23.87
263	20.12	304	21.40	345	22.76	386	23.92
264	20.15	305	21.41	346	22.76	387	23.95
265	20.19	306	21.48	347	22.83	388	24.02
266	20.21	307	21.52	348	22.84	389	24.03
267	20.24	308	21.54	349	22.89	390	24.06
268	20.28	309	21.61	350	22.90	391	24.10
269	20.31	310	21.64	351	22.96	392	24.12
270	20.36	311	21.67	352	22.96	393	24.13
271	20.39	312	21.71	353	22.99	394	24.16
272	20.38	313	21.71	354	23.04	395	24.19
273	20.44	314	21.75	355	23.07	396	24.25
274	20.48	315	21.78	356	23.10	397	24.27
275	20.52	316	21.83	357	23.13	398	24.27

t (min)	s (ft)
399	24.25
400	24.29
401	24.32
402	24.35
403	24.36
404	24.42

t (min)	s (ft)
405	24.42
406	24.46
407	24.48
408	24.52
409	24.56
410	24.59

t (min)	s (ft)
411	24.63
412	24.65
413	24.66
414	24.73
415	24.76
416	24.76

t (min)	s (ft)
417	24.79
418	24.80
419	24.83
420	24.86
421	24.89

A-9. Analysis of Pumping Test, R-9i (Theis)

Test date: 11 Apr 00

Aquifer Data

Saturated thickness: 61.9 ft
Anisotropy ratio (Kz/Kr): 1

Well Data

Pumping well: R-9iP
X = 0 ft
Y = 0 ft

Solution

Analytical method: Theis
Conceptual model: unconfined
T = 49.4 ft^2/d
S = 0.58

A-10. Analysis of Pumping Test, R-9i (Neuman, early-time data)

Test Date: 11 Apr 00

Aquifer Data

Saturated thickness: 61.9 ft
Anisotropy ratio (Kz/Kr): 1

Well Data

Pumping well: R-9i
X = 0 ft
Y = 0 ft

Observation well: R-9i
X = 1.0 ft
Y = 0 ft

Solution

Analytical method: Neuman
Conceptual model: unconfined
T = 315.3 ft^2/d
S = 6.0×10^{-3}
Sy = 0.038
ß = 0.004

A-11. Analysis of Pumping Test, R-9i (Neuman, late-time data)

Test Date: 11 Apr 00

Aquifer Data

Saturated thickness: 61.9 ft
Anisotropy ratio (Kz/Kr): 1

Well Data

Pumping well: R-9i
X = 0 ft
Y = 0 ft

Observation well: R-9i
X = 1.0 ft
Y = 0 ft

Solution

Analytical method: Neuman
Conceptual model: unconfined
T = 13.2 ft^2/d
S = 0.009
Sy = 3.16
ß = 1.5

Appendix B

Well R-13 Test Data

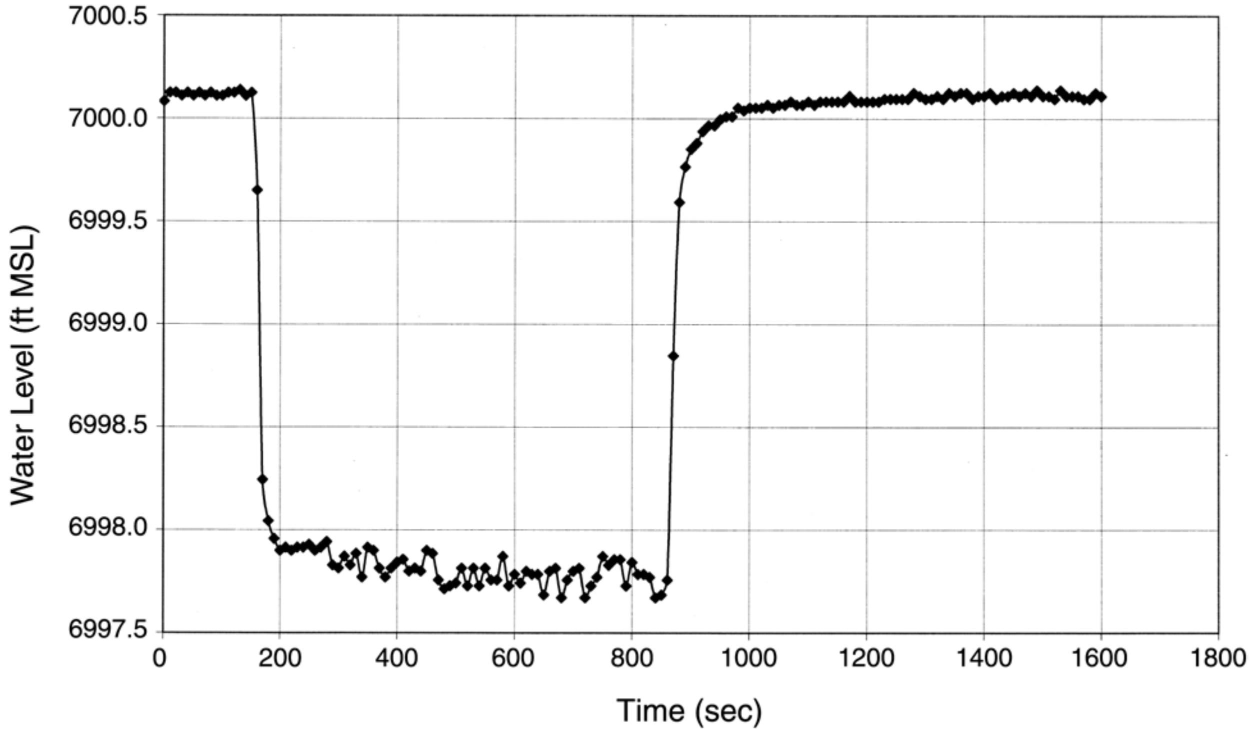
Contents

B-1 Plot for Pumping Test

B-2 Recovery Data for Pumping Test

B-3 Analysis of Pumping Test

B-1. Plot for Pumping Test, R-13b



B-2. Recovery Data for Pumping Test, R-13b

t (sec)	s (ft)	t (sec)	s (ft)	t (sec)	s (ft)	t (sec)	s (ft)
10.000	1.069	200.000	2.289	390.000	2.318	570.000	2.332
20.000	1.816	210.000	2.304	400.000	2.318	580.000	2.332
30.000	1.988	220.000	2.289	410.000	2.318	590.000	2.347
40.000	2.074	230.000	2.289	420.000	2.347	600.000	2.332
50.000	2.103	240.000	2.304	430.000	2.332	610.000	2.347
60.000	2.160	250.000	2.289	440.000	2.318	620.000	2.332
70.000	2.189	260.000	2.304	450.000	2.318	630.000	2.361
80.000	2.189	270.000	2.304	460.000	2.332	640.000	2.332
90.000	2.218	280.000	2.304	470.000	2.318	650.000	2.332
100.000	2.232	290.000	2.304	480.000	2.347	660.000	2.318
110.000	2.232	300.000	2.304	490.000	2.332	670.000	2.361
120.000	2.275	310.000	2.332	500.000	2.347	680.000	2.332
130.000	2.261	320.000	2.304	510.000	2.347	690.000	2.332
140.000	2.275	330.000	2.304	550.000	2.347	730.000	2.347
150.000	2.275	370.000	2.318	560.000	2.318	740.000	2.332
190.000	2.289	380.000	2.318				

B-3. Analysis of Pumping Test, R-13b

Test Date: 27 July 00

Aquifer Data

Saturated thickness:	87.5 ft
Anisotropy ratio (Kz/Kr):	1

Well Data

Pumping well:	R-13
X =	0 ft
Y =	0 ft
Observation well:	R-13
X =	1.0 ft
Y =	0 ft

Solution

Analytical method: Hantush-Jacob

Conceptual model: leaky confined

Pumping:

$T = 1293.3\ ft^2/d$

$S = 1.43 \times 10^{-3}$

r/B = 0.0166

b = 87.5

Recovery:

$T = 829.7\ ft^2/d$

$S = 8.8 \times 10^{-3}$

R/B = 0.10

b = 87.5

Note: *Drawdown and recovery data for the pumping test at R-13 appear almost identical, except the drawdown data are more "noisy." As only data for which an analytical plot appears in the text are included in the appendix, drawdown data for R-13 are not presented.*

Appendix C

Well R-19 Test Data

Contents

C-1 Plot for Injection Test, Screen 6

C-2 Recovery Data for Injection Test, Screen 6

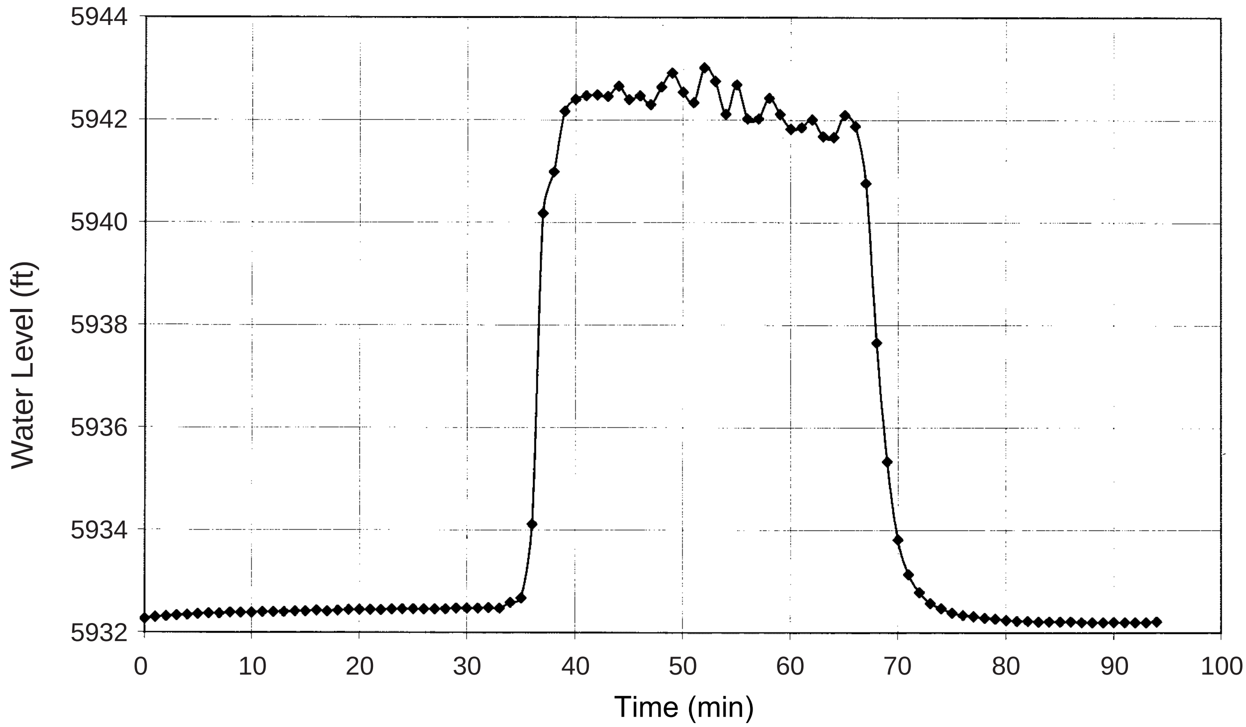
C-3 Analysis of Injection Test, Screen 6

C-4 Plot for Injection Test, Screen 7

C-5 Recovery Data for Injection Test, Screen 7

C-6 Analysis of Injection Test, Screen 7

C-1. Plot for Injection Test, R-19, Screen 6



C-2. Recovery Data for Injection Test, R-19, Screen 6

t (min)	s (ft)
1	8.564
2	5.452
3	3.133
4	1.607
5	0.930
6	0.584
7	0.368
8	0.267
9	0.181
10	0.138
11	0.109
12	0.080
13	0.066
14	0.037
15	0.022
16	0.022

C-3. Analysis of Injection Test, R-19, Screen 6

Test Date: **26 July 00**

Aquifer Data

Saturated thickness:	103.9 ft
Anisotropy ratio (Kz/Kr):	1

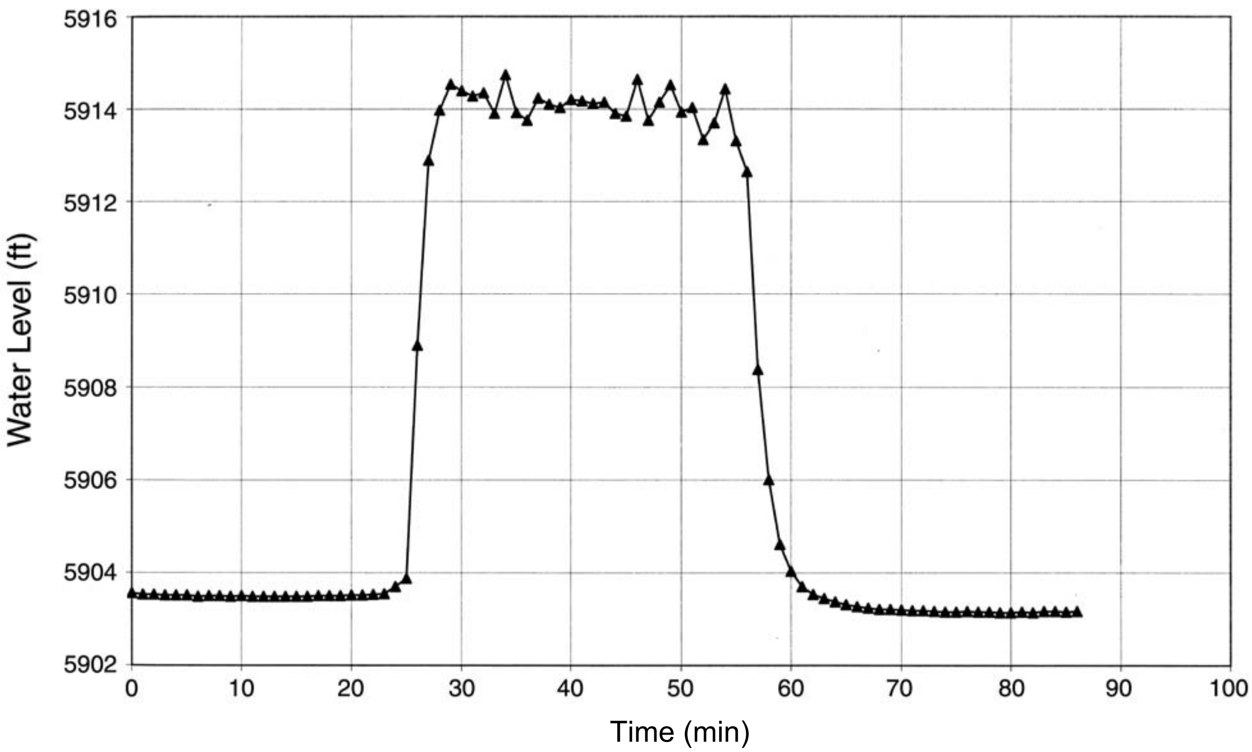
Well Data

Initial displacement:	9.9 ft
Depth of penetration:	58.0 ft
Casing radius:	0.0990 ft
Borehole radius:	0.5104 ft
Screen length:	7.1 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	1.10 ft/d
y_0 =	14.62 ft

C-4. Plot of Injection Test, R-19, Screen 7



C-5. Recovery Data for Injection Test, R-19, Screen 7

t (min)	s (ft)
1	10.155
2	9.492
3	5.228
4	2.852
5	1.454
6	0.878
7	0.547
8	0.374
9	0.288
10	0.216
11	0.158
12	0.115
13	0.086
14	0.057

C-6. Analysis of Injection Test, R-19, Screen 7

Test Date: 26 July 00

Aquifer Data

Saturated thickness:	20.2 ft
Anisotropy ratio (Kz/Kr):	1

Well Data

Initial displacement:	10.9 ft
Depth of penetration:	11.3 ft
Casing radius:	0.0990 ft
Borehole radius:	0.5104 ft
Screen length:	7.1 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	0.73 ft/d
y_0 =	12.95 ft

Appendix D

Well R-22 Test Data

Contents

D-1 Plot for Injection Test, Screen 2

D-2 Recovery Data for Injection Test, Screen 2

D-3 Analysis of Injection Test, Screen 2

D-4 Plot for Injection Test, Screen 3

D-5 Recovery Data for Injection Test, Screen 3

D-6 Analysis of Injection Test, Screen 3

D-7 Plot for Injection Test, Screen 4a

D-8 Recovery Data for Injection Test, Screen 4a

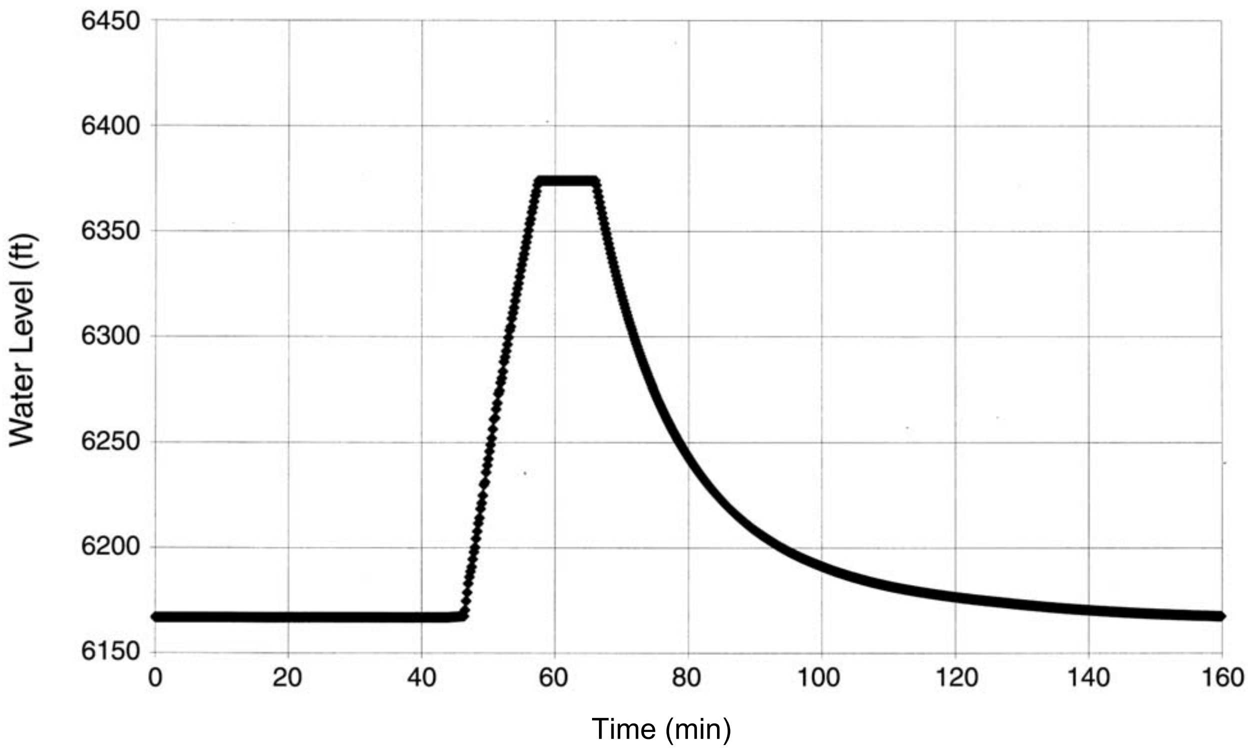
D-9 Analysis of Injection Test, Screen 4a

D-10 Plot for Injection Test, Screen 5

D-11 Recovery Data for Injection Test, Screen 5

D-12 Analysis of Injection Test, Screen 5

D-1. Plot for Injection Test, R-22, Screen 2



D-2. Recovery Data for Injection Test, R-22, Screen 2

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
0.000	276.862	2.833	224.194	5.667	179.527	8.500	144.799
0.167	275.004	3.000	221.303	5.833	177.214	8.667	143.007
0.333	271.576	3.167	218.447	6.000	174.944	8.833	141.274
0.500	268.182	3.333	215.623	6.167	172.660	9.000	139.584
0.667	264.823	3.500	212.832	6.333	170.477	9.167	137.879
0.833	261.496	3.667	210.076	6.500	168.309	9.333	136.363
1.000	258.203	3.833	207.353	6.667	166.199	9.500	134.557
1.167	254.945	4.000	204.891	6.833	164.046	9.667	132.925
1.333	251.718	4.167	202.114	7.000	161.994	9.833	131.365
1.500	248.525	4.333	199.438	7.167	159.970	10.000	129.805
1.667	245.368	4.500	196.806	7.333	157.976	10.167	128.260
1.833	242.242	4.667	194.203	7.500	156.025	10.333	126.744
2.000	239.150	4.833	191.643	7.667	154.031	10.500	125.242
2.167	236.093	5.000	189.156	7.833	152.124	10.667	123.740
2.333	233.067	5.167	186.712	8.000	150.246	10.833	122.267
2.500	230.075	5.333	184.254	8.167	148.411	11.000	120.852
2.667	227.119	5.500	181.840	8.333	146.605	11.167	119.437
11.333	118.051	18.167	74.248	25.000	48.662	31.833	33.035
11.500	116.679	18.333	73.454	25.167	48.187	32.000	32.747

t (min)	s (ft)
11.667	115.322
11.833	113.878
12.000	112.607
12.167	111.279
12.333	109.994
12.500	108.738
12.667	107.468
12.833	106.226
13.000	104.999
13.167	103.772
13.333	102.589
13.500	101.434
13.667	100.279
13.833	99.139
14.000	98.013
14.167	96.916
14.333	95.834
14.500	94.737
14.667	93.640
14.833	92.587
15.000	91.562
15.167	90.538
15.333	89.527
15.500	88.546
15.667	87.565
15.833	86.613
16.000	85.617
16.167	84.564
16.333	83.712
16.500	82.803
16.667	81.909
16.833	81.029
17.000	80.134
17.167	79.268
17.333	78.417
17.500	77.580
17.667	76.744
17.833	75.907
18.000	75.084
38.667	23.278
38.833	23.076

t (min)	s (ft)
18.500	72.675
18.667	71.911
18.833	71.146
19.000	70.396
19.167	69.660
19.333	68.925
19.500	68.218
19.667	67.497
19.833	66.804
20.000	66.112
20.167	65.405
20.333	64.713
20.500	64.021
20.667	63.357
20.833	62.708
21.000	62.059
21.167	61.410
21.333	60.776
21.500	60.170
21.667	59.535
21.833	58.944
22.000	58.338
22.167	57.761
22.333	57.170
22.500	56.593
22.667	56.017
22.833	55.454
23.000	54.863
23.167	54.300
23.333	53.738
23.500	53.205
23.667	52.685
23.833	52.152
24.000	51.633
24.167	51.128
24.333	50.609
24.500	50.119
24.667	49.643
24.833	49.138
45.500	16.692
45.667	16.563

t (min)	s (ft)
25.333	47.740
25.500	47.264
25.667	46.803
25.833	46.356
26.000	45.909
26.167	45.462
26.333	45.015
26.500	44.553
26.667	44.121
26.833	43.674
27.000	43.270
27.167	42.852
27.333	42.448
27.500	42.030
27.667	41.641
27.833	41.252
28.000	40.863
28.167	40.488
28.333	40.099
28.500	39.738
28.667	39.363
28.833	39.003
29.000	38.628
29.167	38.268
29.333	37.936
29.500	37.576
29.667	37.230
29.833	36.884
30.000	36.552
30.167	36.206
30.333	35.889
30.500	35.558
30.667	35.241
30.833	34.909
31.000	34.578
31.167	34.246
31.333	33.929
31.500	33.626
31.667	33.338
52.333	12.312
52.500	12.226

t (min)	s (ft)
32.167	32.459
32.333	32.185
32.500	31.897
32.667	31.608
32.833	31.334
33.000	31.075
33.167	30.801
33.333	30.513
33.500	30.253
33.667	30.008
33.833	29.735
34.000	29.489
34.167	29.230
34.333	28.971
34.500	28.740
34.667	28.495
34.833	28.250
35.000	28.034
35.167	27.789
35.333	27.558
35.500	27.328
35.667	27.111
35.833	26.881
36.000	26.650
36.167	26.434
36.333	26.203
36.500	26.002
36.667	25.786
36.833	25.569
37.000	25.353
37.167	25.137
37.333	24.921
37.500	24.705
37.667	24.503
37.833	24.287
38.000	24.085
38.167	23.869
38.333	23.681
38.500	23.480
59.167	9.143
59.333	9.085

t (min)	s (ft)
39.000	22.889
39.167	22.687
39.333	22.514
39.500	22.327
39.667	22.139
39.833	21.952
40.000	21.779
40.167	21.592
40.333	21.419
40.500	21.246
40.667	21.073
40.833	20.900
41.000	20.742
41.167	20.583
41.333	20.396
41.500	20.237
41.667	20.064
41.833	19.906
42.000	19.733
42.167	19.574
42.333	19.401
42.500	19.257
42.667	19.113
42.833	18.955
43.000	18.811
43.167	18.667
43.333	18.508
43.500	18.364
43.667	18.205
43.833	18.061
44.000	17.932
44.167	17.773
44.333	17.643
44.500	17.514
44.667	17.370
44.833	17.226
45.000	17.081
45.167	16.952
45.333	16.822
66.000	6.737
66.167	6.679

t (min)	s (ft)
45.833	16.447
46.000	16.303
46.167	16.188
46.333	16.058
46.500	15.929
46.667	15.813
46.833	15.698
47.000	15.569
47.167	15.453
47.333	15.338
47.500	15.223
47.667	15.093
47.833	14.992
48.000	14.877
48.167	14.762
48.333	14.646
48.500	14.546
48.667	14.430
48.833	14.315
49.000	14.229
49.167	14.113
49.333	14.012
49.500	13.912
49.667	13.811
49.833	13.724
50.000	13.609
50.167	13.523
50.333	13.422
50.500	13.321
50.667	13.220
50.833	13.119
51.000	13.033
51.167	12.946
51.333	12.845
51.500	12.744
51.667	12.672
51.833	12.572
52.000	12.471
52.167	12.399
72.833	4.662
73.000	4.619

t (min)	s (ft)
52.667	12.125
52.833	12.038
53.000	11.952
53.167	11.880
53.333	11.779
53.500	11.693
53.667	11.606
53.833	11.534
54.000	11.462
54.167	11.361
54.333	11.289
54.500	11.217
54.667	11.131
54.833	11.059
55.000	10.958
55.167	10.871
55.333	10.814
55.500	10.742
55.667	10.641
55.833	10.569
56.000	10.497
56.167	10.425
56.333	10.353
56.500	10.266
56.667	10.194
56.833	10.122
57.000	10.065
57.167	9.964
57.333	9.921
57.500	9.849
57.667	9.762
57.833	9.704
58.000	9.632
58.167	9.560
58.333	9.488
58.500	9.416
58.667	9.359
58.833	9.287
59.000	9.229
79.667	3.092
79.833	3.049

t (min)	s (ft)
59.500	9.013
59.667	8.955
59.833	8.898
60.000	8.840
60.167	8.754
60.333	8.696
60.500	8.624
60.667	8.581
60.833	8.523
61.000	8.451
61.167	8.379
61.333	8.321
61.500	8.264
61.667	8.206
61.833	8.149
62.000	8.091
62.167	8.019
62.333	7.961
62.500	7.918
62.667	7.846
62.833	7.803
63.000	7.745
63.167	7.688
63.333	7.630
63.500	7.572
63.667	7.529
63.833	7.471
64.000	7.428
64.167	7.371
64.333	7.327
64.500	7.255
64.667	7.198
64.833	7.140
65.000	7.082
65.167	7.025
65.333	6.967
65.500	6.895
65.667	6.838
65.833	6.780
86.500	1.896
86.667	1.868

t (min)	s (ft)
66.333	6.621
66.500	6.564
66.667	6.506
66.833	6.449
67.000	6.405
67.167	6.348
67.333	6.290
67.500	6.247
67.667	6.175
67.833	6.132
68.000	6.074
68.167	6.031
68.333	5.973
68.500	5.930
68.667	5.887
68.833	5.800
69.000	5.757
69.167	5.714
69.333	5.671
69.500	5.613
69.667	5.570
69.833	5.512
70.000	5.483
70.167	5.411
70.333	5.368
70.500	5.310
70.667	5.267
70.833	5.224
71.000	5.181
71.167	5.123
71.333	5.080
71.500	5.022
71.667	4.979
71.833	4.936
72.000	4.893
72.167	4.849
72.333	4.806
72.500	4.763
72.667	4.720
93.333	1.003
93.500	1.003

t (min)	s (ft)
73.167	4.590
73.333	4.533
73.500	4.504
73.667	4.446
73.833	4.403
74.000	4.374
74.167	4.316
74.333	4.273
74.500	4.244
74.667	4.201
74.833	4.158
75.000	4.129
75.167	4.086
75.333	4.043
75.500	4.000
75.667	3.971
75.833	3.913
76.000	3.884
76.167	3.827
76.333	3.798
76.500	3.769
76.667	3.726
76.833	3.683
77.000	3.654
77.167	3.611
77.333	3.567
77.500	3.539
77.667	3.495
77.833	3.467
78.000	3.438
78.167	3.395
78.333	3.366
78.500	3.337
78.667	3.279
78.833	3.250
79.000	3.207
79.167	3.178
79.333	3.150
79.500	3.121
94.500	0.874
94.667	0.859

t (min)	s (ft)
80.000	3.020
80.167	2.991
80.333	2.962
80.500	2.934
80.667	2.905
80.833	2.847
81.000	2.818
81.167	2.804
81.333	2.761
81.500	2.732
81.667	2.703
81.833	2.660
82.000	2.631
82.167	2.602
82.333	2.573
82.500	2.559
82.667	2.530
82.833	2.473
83.000	2.444
83.167	2.415
83.333	2.386
83.500	2.372
83.667	2.329
83.833	2.314
84.000	2.285
84.167	2.257
84.333	2.228
84.500	2.213
84.667	2.170
84.833	2.156
85.000	2.112
85.167	2.084
85.333	2.055
85.500	2.040
85.667	2.012
85.833	1.983
86.000	1.954
86.167	1.940
86.333	1.911
95.667	0.773
95.833	0.758

t (min)	s (ft)
86.833	1.839
87.000	1.810
87.167	1.796
87.333	1.752
87.500	1.724
87.667	1.709
87.833	1.695
88.000	1.652
88.167	1.652
88.333	1.623
88.500	1.608
88.667	1.580
88.833	1.565
89.000	1.536
89.167	1.522
89.333	1.493
89.500	1.479
89.667	1.450
89.833	1.435
90.000	1.421
90.167	1.392
90.333	1.363
90.500	1.349
90.667	1.320
90.833	1.306
91.000	1.291
91.167	1.263
91.333	1.234
91.500	1.219
91.667	1.205
91.833	1.191
92.000	1.176
92.167	1.147
92.333	1.133
92.500	1.119
92.667	1.090
92.833	1.075
93.000	1.061
93.167	1.032
96.833	0.629
97.000	0.643

t (min)	s (ft)
93.667	0.975
93.833	0.960
94.000	0.946
94.167	0.917
94.333	0.902

t (min)	s (ft)
94.833	0.845
95.000	0.830
95.167	0.830
95.333	0.816
95.500	0.802

t (min)	s (ft)
96.000	0.744
96.167	0.730
96.333	0.715
96.500	0.701
96.667	0.686

t (min)	s (ft)
97.167	0.629
97.333	0.614
97.500	0.600
97.667	0.600

D-3. Analysis of Injection Test, R-22, Screen 2

Test Date: 15 Nov 00

Aquifer Data

Saturated thickness:	69.5 ft
Anisotropy ratio (Kz/Kr):	1

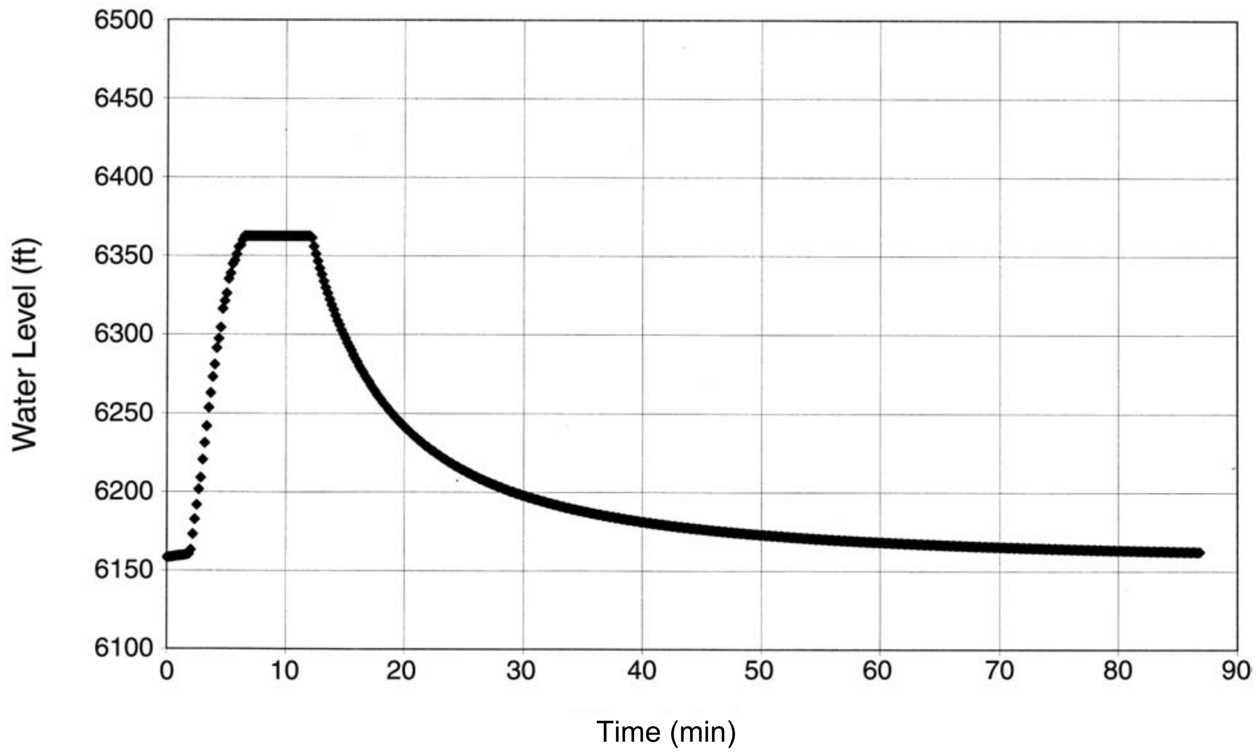
Well Data

Initial displacement:	276.9 ft
Depth of penetration:	51.4 ft
Casing radius:	0.0990 ft
Borehole radius:	0.5104 ft
Screen length:	41.9 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	0.036 ft/d
y_0 =	266.8 ft

D-4. Plot for Injection Test, R-22, Screen 3



D-5. Recovery Data for Injection Test, R-22, Screen 3

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
0.000	313.571	3.000	202.215	6.000	135.375	9.000	97.861
0.167	306.154	3.167	196.704	6.167	132.905	9.167	96.374
0.333	298.874	3.333	192.047	6.333	130.666	9.333	95.061
0.500	291.737	3.500	187.405	6.500	127.864	9.500	93.199
0.667	284.746	3.667	182.850	6.667	125.626	9.667	91.770
0.833	277.892	3.833	178.816	6.833	123.589	9.833	90.514
1.000	271.181	4.000	174.595	7.000	120.961	10.000	88.811
1.167	264.615	4.167	170.562	7.167	118.881	10.167	87.498
1.333	258.188	4.333	166.962	7.333	117.062	10.333	86.430
1.500	251.903	4.500	163.060	7.500	114.622	10.500	84.756
1.667	245.763	4.667	159.548	7.667	112.745	10.667	83.573
1.833	239.762	4.833	156.426	7.833	110.969	10.833	82.505
2.000	233.902	5.000	152.828	8.000	108.601	11.000	80.961
2.167	228.188	5.167	149.447	8.167	106.768	11.167	79.937
2.333	222.613	5.333	146.774	8.333	105.136	11.333	78.783
2.500	217.180	5.500	143.508	8.500	102.942	11.500	77.441
2.667	211.892	5.667	140.778	8.667	101.267	11.667	76.489
2.833	206.742	5.833	138.351	8.833	99.853	11.833	75.464

t (min)	s (ft)
12.000	74.137
12.167	73.228
12.333	72.305
12.500	70.977
12.667	69.982
12.833	69.362
13.000	68.063
13.167	67.212
13.333	66.563
13.500	65.323
13.667	64.515
13.833	63.938
14.000	62.784
14.167	61.919
14.333	61.370
14.500	60.289
14.667	59.524
14.833	59.048
15.000	57.981
15.167	57.274
15.333	56.798
15.500	55.875
15.667	55.125
15.833	54.693
16.000	53.871
16.167	53.092
16.333	52.659
16.500	51.866
16.667	51.131
16.833	50.727
17.000	50.064
17.167	49.314
17.333	48.896
17.500	48.377
17.667	47.584
17.833	47.165
18.000	46.762
18.167	45.954
18.333	45.565
18.500	45.204
18.667	44.383

t (min)	s (ft)
18.833	44.008
19.000	43.719
19.167	42.912
19.333	42.551
19.500	42.278
19.667	41.456
19.833	41.110
20.000	40.937
20.167	40.115
20.333	39.769
20.500	39.639
20.667	38.846
20.833	38.515
21.000	38.385
21.167	37.678
21.333	37.289
21.500	37.188
21.667	36.568
21.833	36.150
22.000	36.035
22.167	35.502
22.333	35.040
22.500	34.882
22.667	34.507
22.833	33.959
23.000	33.757
23.167	33.555
23.333	32.936
23.500	32.734
23.667	32.604
23.833	31.941
24.000	31.710
24.167	31.682
24.333	31.004
24.500	30.773
24.667	30.788
24.833	30.139
25.000	29.909
25.167	29.909
25.333	29.332
25.500	29.044

t (min)	s (ft)
25.667	29.029
25.833	28.582
26.000	28.237
26.167	28.237
26.333	27.819
26.500	27.444
26.667	27.372
26.833	27.156
27.000	26.694
27.167	26.579
27.333	26.550
27.500	25.959
27.667	25.844
27.833	25.887
28.000	25.282
28.167	25.152
28.333	25.239
28.500	24.633
28.667	24.504
28.833	24.590
29.000	23.999
29.167	23.869
29.333	23.941
29.500	23.437
29.667	23.235
29.833	23.307
30.000	22.947
30.167	22.630
30.333	22.616
30.500	22.443
30.667	22.010
30.833	21.938
31.000	21.953
31.167	21.434
31.333	21.362
31.500	21.463
31.667	20.915
31.833	20.800
32.000	20.901
32.167	20.483
32.333	20.281

t (min)	s (ft)
32.500	20.353
32.667	20.079
32.833	19.762
33.000	19.805
33.167	19.647
33.333	19.272
33.500	19.258
33.667	19.258
33.833	18.796
34.000	18.768
34.167	18.869
34.333	18.364
34.500	18.307
34.667	18.451
34.833	17.961
35.000	17.874
35.167	18.033
35.333	17.572
35.500	17.442
35.667	17.572
35.833	17.226
36.000	17.024
36.167	17.125
36.333	16.909
36.500	16.635
36.667	16.721
36.833	16.563
37.000	16.231
37.167	16.303
37.333	16.260
37.500	15.871
37.667	15.871
37.833	15.958
38.000	15.496
38.167	15.482
38.333	15.655
38.500	15.165
38.667	15.136
38.833	15.309
39.000	14.891
39.167	14.776

t (min)	s (ft)
39.333	14.935
39.500	14.603
39.667	14.445
39.833	14.560
40.000	14.373
40.167	14.113
40.333	14.171
40.500	14.128
40.667	13.782
40.833	13.811
41.000	13.883
41.167	13.465
41.333	13.494
41.500	13.652
41.667	13.177
41.833	13.177
42.000	13.378
42.167	12.903
42.333	12.903
42.500	13.090
42.667	12.672
42.833	12.600
43.000	12.787
43.167	12.470
43.333	12.312
43.500	12.456
43.667	12.283
43.833	12.024
44.000	12.110
44.167	12.081
44.333	11.736
44.500	11.779
44.667	11.909
44.833	11.476
45.000	11.491
45.167	11.707
45.333	11.246
45.500	11.231
45.667	11.447
45.833	11.087
46.000	10.986

t (min)	s (ft)
46.167	11.130
46.333	10.972
46.500	10.741
46.667	10.799
46.833	10.871
47.000	10.482
47.167	10.540
47.333	10.713
47.500	10.280
47.667	10.280
47.833	10.525
48.000	10.093
48.167	10.064
48.333	10.280
48.500	9.992
48.667	9.848
48.833	9.978
49.000	9.863
49.167	9.646
49.333	9.747
49.500	9.704
49.667	9.430
49.833	9.473
50.000	9.618
50.167	9.229
50.333	9.257
50.500	9.473
50.667	9.084
50.833	9.056
51.000	9.257
51.167	8.984
51.333	8.854
51.500	8.984
51.667	8.926
51.833	8.652
52.000	8.710
52.167	8.840
52.333	8.451
52.500	8.494
52.667	8.724
52.833	8.321

t (min)	s (ft)
53.000	8.306
53.167	8.508
53.333	8.263
53.500	8.119
53.667	8.263
53.833	8.206
54.000	7.932
54.167	8.004
54.333	8.119
54.500	7.759
54.667	7.831
54.833	8.018
55.000	7.615
55.167	7.644
55.333	7.860
55.500	7.543
55.667	7.471
55.833	7.629
56.000	7.500
56.167	7.283
56.333	7.356
56.500	7.485
56.667	7.125
56.833	7.168
57.000	7.384
57.167	6.981
57.333	6.995
57.500	7.240
57.667	6.866
57.833	6.851
58.000	7.082
58.167	6.822
58.333	6.707
58.500	6.808
58.667	6.822
58.833	6.534
59.000	6.606
59.167	6.779
59.333	6.390
59.500	6.448
59.667	6.664

t (min)	s (ft)
59.833	6.275
60.000	6.304
60.167	6.534
60.333	6.203
60.500	6.160
60.667	6.361
60.833	6.145
61.000	6.030
61.167	6.174
61.333	6.073
61.500	5.872
61.667	6.001
61.833	6.073
62.000	5.742
62.167	5.800
62.333	6.016
62.500	5.627
62.667	5.670
62.833	5.900
63.000	5.526
63.167	5.526
63.333	5.742
63.500	5.483
63.667	5.396
63.833	5.511
64.000	5.497
64.167	5.266
64.333	5.353
64.500	5.483
64.667	5.122
64.833	5.194
65.000	5.425
65.167	5.050
65.333	5.050
65.500	5.295
65.667	5.036
65.833	4.950
66.000	5.094
66.167	5.007
66.333	4.820
66.500	4.906

t (min)	s (ft)
66.667	5.036
66.833	4.690
67.000	4.748
67.167	4.993
67.333	4.633
67.500	4.618
67.667	4.834
67.833	4.647
68.000	4.474
68.167	4.532
68.333	4.690
68.500	4.359
68.667	4.431
68.833	4.661
69.000	4.301
69.167	4.301
69.333	4.546

t (min)	s (ft)
69.500	4.287
69.667	4.186
69.833	4.316
70.000	4.359
70.167	4.071
70.333	4.143
70.500	4.359
70.667	3.999
70.833	4.013
71.000	4.258
71.167	4.056
71.333	3.898
71.500	4.028
71.667	4.143
71.833	3.783
72.000	3.840
72.167	4.100

t (min)	s (ft)
72.333	3.768
72.500	3.739
72.667	3.898
72.833	3.855
73.000	3.610
73.167	3.711
73.333	3.898
73.500	3.523
73.667	3.566
73.833	3.826
74.000	3.566
74.167	3.466
74.333	3.595
74.500	3.639
74.667	3.365
74.833	3.437
75.000	3.667

t (min)	s (ft)
75.167	3.293
75.333	3.336
75.500	3.581
75.667	3.307
75.833	3.221
76.000	3.394
76.167	3.394
76.333	3.134
76.500	3.221
76.667	3.408
76.833	3.048
77.000	3.105
77.167	3.365
77.333	3.048
77.500	3.019
77.667	3.192
77.833	3.134

D-6. Analysis of Injection Test, R-22, Screen 3

Test Date: 16 Nov 00

Aquifer Data

Saturated thickness:	49.4 ft
Anisotropy ratio (Kz/Kr):	1

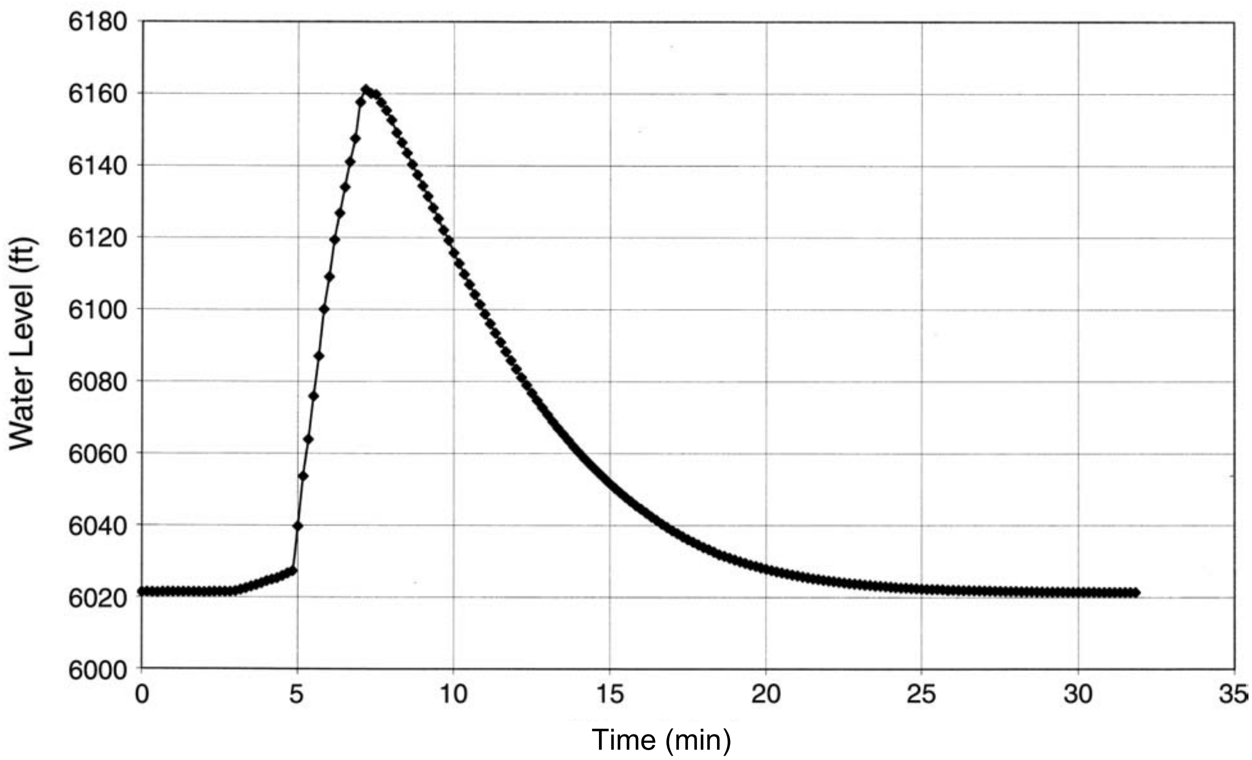
Well Data

Initial displacement:	313.6 ft
Depth of penetration:	44.3 ft
Casing radius:	0.0990 ft
Borehole radius:	0.5104 ft
Screen length:	6.7 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	0.21 ft/d
y_0 =	240.5 ft

D-7. Plot for Injection Test, R-22, Screen 4a



D-8. Recovery Data for Injection Test, R-22, Screen 4a

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
0.000	139.655	3.000	91.320	6.000	47.388	9.000	21.985
0.167	138.585	3.167	88.376	6.167	45.571	9.167	20.932
0.333	138.296	3.333	85.518	6.333	43.826	9.333	19.938
0.500	136.057	3.500	82.747	6.500	42.125	9.500	18.943
0.667	133.861	3.667	79.947	6.667	40.409	9.667	18.021
0.833	131.189	3.833	77.234	6.833	38.794	9.833	17.099
1.000	127.650	4.000	74.594	7.000	37.222	10.000	16.248
1.167	124.948	4.167	71.997	7.167	35.708	10.167	15.427
1.333	122.016	4.333	69.429	7.333	34.252	10.333	14.634
1.500	118.882	4.500	66.846	7.500	32.839	10.500	13.870
1.667	115.936	4.667	64.365	7.667	31.470	10.667	13.150
1.833	112.918	4.833	61.956	7.833	30.086	10.833	12.458
2.000	110.016	5.000	59.619	8.000	28.788	11.000	11.795
2.167	106.796	5.167	57.498	8.167	27.563	11.167	11.147
2.333	103.850	5.333	55.335	8.333	26.367	11.333	10.455
2.500	100.588	5.500	53.272	8.500	25.199	11.500	9.994
2.667	97.758	5.667	51.253	8.667	24.089	11.667	9.475
2.833	94.279	5.833	49.277	8.833	23.022	11.833	8.985

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
12.000	8.481	14.833	3.150	17.500	1.104	20.167	0.311
12.167	8.034	15.000	2.948	17.667	1.003	20.333	0.282
12.333	7.587	15.167	2.775	17.833	0.931	20.500	0.254
12.500	7.184	15.333	2.602	18.000	0.873	20.667	0.225
12.667	6.795	15.500	2.444	18.167	0.815	20.833	0.210
12.833	6.420	15.667	2.299	18.333	0.758	21.000	0.196
13.000	6.060	15.833	2.155	18.500	0.700	21.167	0.167
13.167	5.714	16.000	2.026	18.667	0.571	21.333	0.153
13.333	5.397	16.167	1.910	18.833	0.614	21.500	0.124
13.500	5.095	16.333	1.766	19.000	0.556	21.667	0.095
13.667	4.806	16.500	1.665	19.167	0.498	21.833	0.081
13.833	4.518	16.667	1.550	19.333	0.470	22.000	0.066
14.000	4.259	16.833	1.464	19.500	0.441	22.167	0.052
14.167	4.014	17.000	1.349	19.667	0.398	22.333	0.037
14.333	3.769	17.167	1.190	19.833	0.369	22.500	0.023
14.500	3.553	17.333	1.190	20.000	0.340	22.667	0.009
14.667	3.337						

D-9. Analysis of Injection Test, R-22, Screen 4a

Test Date: 17 Nov 00

Aquifer Data

Saturated thickness:	49.0 ft
Anisotropy ratio (Kz/Kr):	1

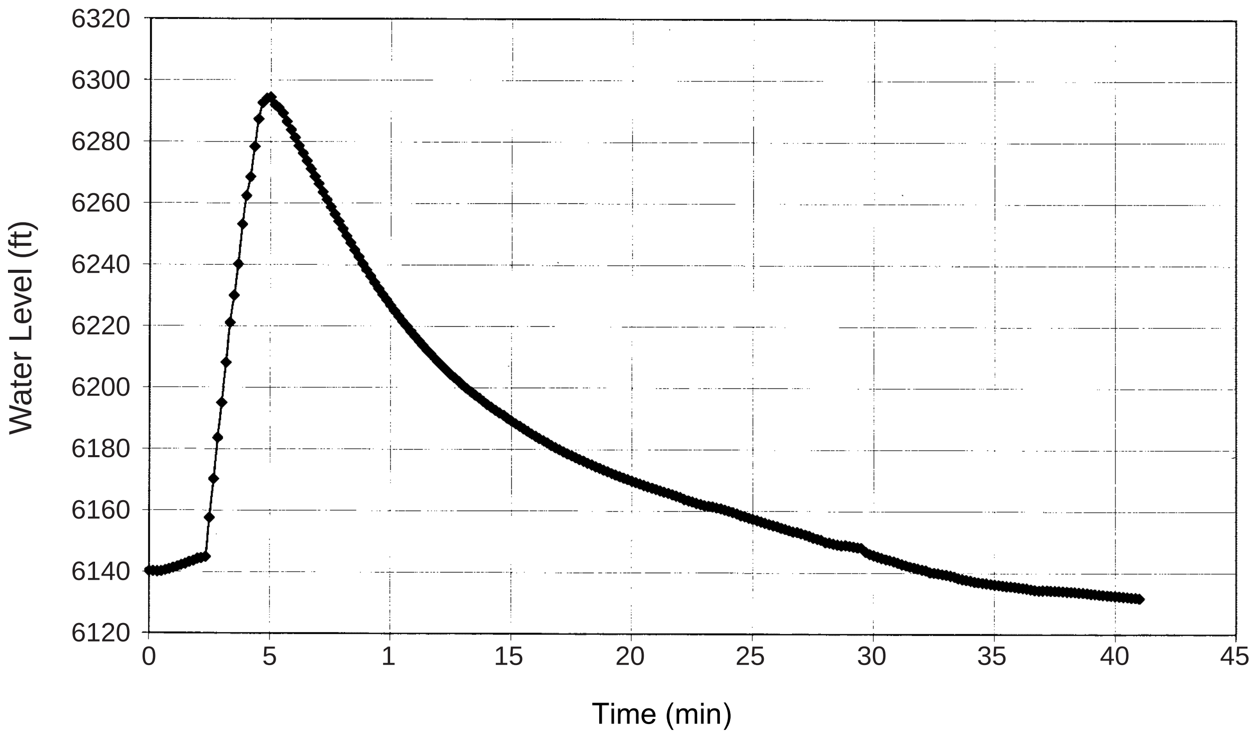
Well Data

Initial displacement:	139.7 ft
Depth of penetration:	44.9 ft
Casing radius:	0.0990 ft
Borehole radius:	0.4375 ft
Screen length:	6.7 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	0.54 ft/d
y_0 =	160.9 ft

D-10. Plot for Injection Test, R-22, Screen 5



D-11. Recovery Data for Injection Test, R-22, Screen 5

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
0.000	154.101	3.000	111.380	6.000	76.399	9.000	54.202
0.167	151.573	3.167	109.027	6.167	74.855	9.167	53.279
0.333	150.648	3.333	106.746	6.333	73.326	9.333	52.371
0.500	148.900	3.500	104.422	6.500	71.927	9.500	51.463
0.667	146.227	3.667	102.199	6.667	70.528	9.667	50.655
0.833	143.540	3.833	100.063	6.833	69.143	9.833	49.761
1.000	140.954	4.000	97.970	7.000	67.816	10.000	48.867
1.167	138.354	4.167	95.950	7.167	66.489	10.167	47.973
1.333	135.841	4.333	93.915	7.333	65.162	10.333	47.166
1.500	133.357	4.500	91.953	7.500	63.936	10.500	46.359
1.667	130.743	4.667	90.077	7.667	62.768	10.667	45.551
1.833	128.331	4.833	88.244	7.833	61.571	10.833	44.715
2.000	125.963	5.000	86.440	8.000	60.446	11.000	43.951
2.167	123.349	5.167	84.695	8.167	59.336	11.167	43.187
2.333	120.880	5.333	82.905	8.333	58.269	11.333	42.466
2.500	118.469	5.500	81.217	8.500	57.274	11.500	41.717
2.667	116.101	5.667	79.587	8.667	56.235	11.667	40.996
2.833	113.748	5.833	77.986	8.833	55.212	11.833	40.261

t (min)	s (ft)
12.000	39.597
12.167	38.920
12.333	38.228
12.500	37.637
12.667	37.017
12.833	36.455
13.000	35.850
13.167	35.244
13.333	34.639
13.500	34.034
13.667	33.500
13.833	32.953
14.000	32.434
14.167	31.929
14.333	31.396
14.500	30.877
14.667	30.387
14.833	29.883
15.000	29.436
15.167	28.946
15.333	28.485
15.500	28.023
15.667	27.591

t (min)	s (ft)
15.833	27.144
16.000	26.698
16.167	26.251
16.333	25.833
16.500	25.429
16.667	24.997
16.833	24.565
17.000	24.147
17.167	23.470
17.333	23.049
17.500	22.660
17.667	22.242
17.833	21.852
18.000	21.506
18.167	21.261
18.333	21.031
18.500	20.786
18.667	20.469
18.833	20.108
19.000	19.705
19.167	19.315
19.333	18.883
19.500	18.335

t (min)	s (ft)
19.667	17.932
19.833	17.485
20.000	17.125
20.167	16.692
20.333	16.274
20.500	15.856
20.667	15.424
20.833	15.020
21.000	14.660
21.167	14.199
21.333	13.810
21.500	13.449
21.667	13.017
21.833	12.859
22.000	12.441
22.167	11.994
22.333	11.561
22.500	11.057
22.667	10.668
22.833	10.308
23.000	9.515
23.167	9.472
23.333	9.097

t (min)	s (ft)
23.500	8.838
23.667	8.578
23.833	8.622
24.000	8.377
24.167	8.117
24.333	7.887
24.500	7.728
24.667	6.489
24.833	5.797
25.000	5.350
25.167	4.904
25.333	4.500
25.500	4.097
25.667	3.751
25.833	3.333
26.000	2.915
26.167	2.469
26.333	2.094
26.500	1.691
26.667	1.359
26.833	0.999
27.000	0.696
27.167	0.480

D-12. Analysis of Injection Test, R-22, Screen 5

Test Date: 17 Aug 00

Aquifer Data

Saturated thickness:	43.0 ft
Anisotropy ratio (Kz/Kr):	1

Well Data

Initial displacement:	154.1 ft
Depth of penetration:	17.3 ft
Casing radius:	0.0990 ft
Borehole radius:	0.4375 ft
Screen length:	5 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	0.27 ft/d
y_0 =	153.6 ft

Appendix E

Well R-31 Test Data

Contents

E-1 Plot for Injection Tests, Screen 3

E-2 Recovery Data for Injection Test, Screen 3a

E-3 Analysis of Injection Test, Screen 3a

E-4 Plot for Injection Test, Screen 4

E-5 Recovery Data for Injection Test, Screen 4

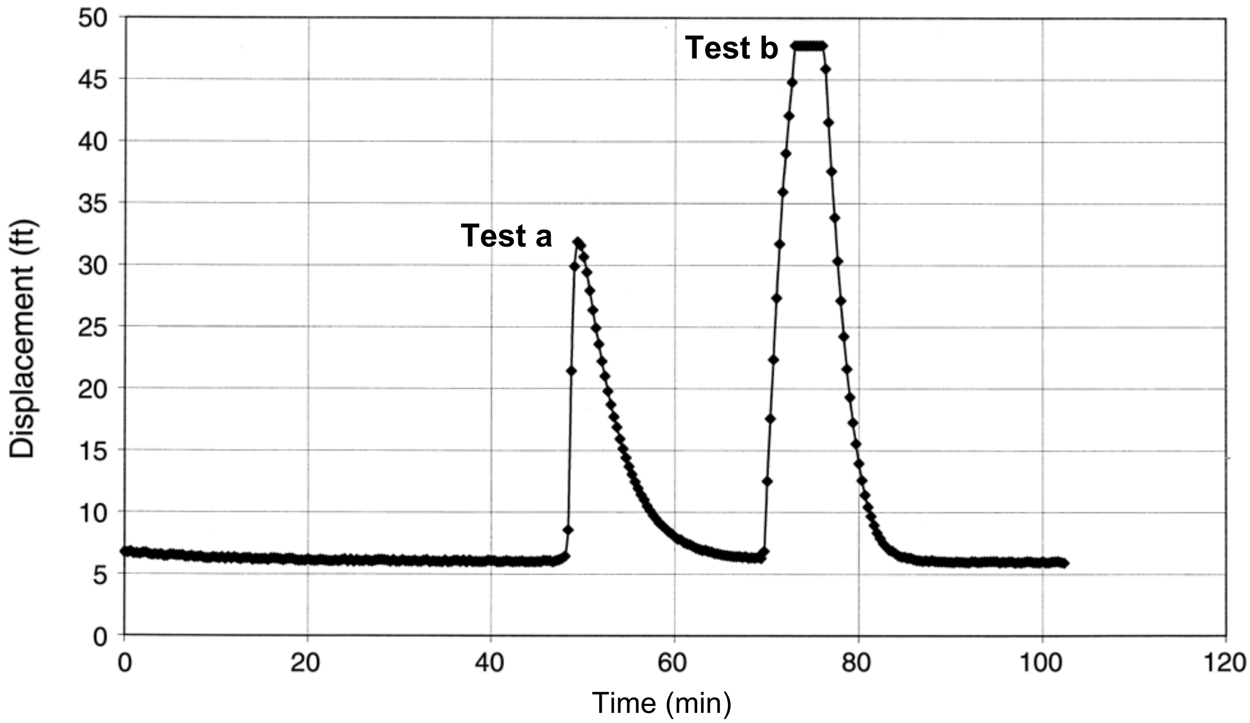
E-6 Analysis of Injection Test, Screen 4

E-7 Plot for Injection Test, Screen 5

E-8 Recovery Data for Injection Test, Screen 5

E-9 Analysis of Injection Test, Screen 5

E-1. Plot for Injection Tests, R-31, Screen 3



E-2. Recovery Data for Injection Test, R-31, Screen 3a

t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)	t (min)	s (ft)
0.000	25.825	5.333	8.348	10.667	1.963	15.667	0.512
0.333	25.517	5.667	7.631	11.000	1.764	16.000	0.472
0.667	24.606	6.000	7.007	11.333	1.709	16.333	0.435
1.000	23.369	6.333	6.392	11.667	1.501	16.667	0.394
1.333	21.869	6.667	5.864	12.000	1.383	17.000	0.363
1.667	20.303	7.000	5.359	12.333	1.317	17.333	0.342
2.000	18.847	7.333	4.940	12.667	1.173	17.667	0.357
2.333	17.529	7.667	4.429	13.000	1.026	18.000	0.299
2.667	16.150	8.000	4.060	13.333	0.948	18.333	0.345
3.000	14.954	8.333	3.685	13.667	0.858	18.667	0.233
3.333	13.724	8.667	3.402	14.000	0.881	19.000	0.279
3.667	12.653	9.000	3.062	14.333	0.763	19.333	0.239
4.000	11.661	9.333	2.863	14.667	0.734	19.667	0.285
4.333	10.825	9.667	2.623	15.000	0.605	20.000	0.227
4.667	9.874	10.000	2.372	15.333	0.584	20.333	0.780
5.000	9.070	10.333	2.196				

E-3. Analysis of Injection Test, R-31, Screen 3a

Test Date: 18 Mar 00

Aquifer Data

Saturated thickness:	18.0 ft
Anisotropy ratio (Kz/Kr):	1

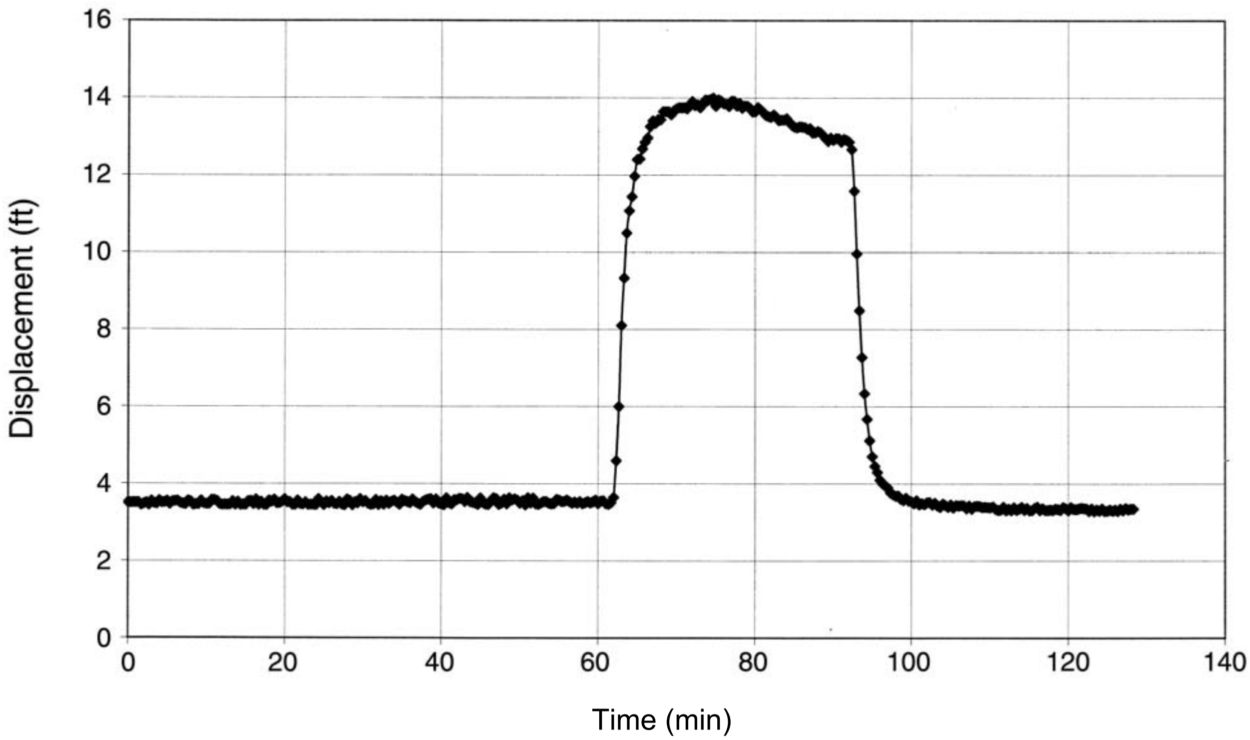
Well Data

Initial displacement:	25.8 ft
Depth of penetration:	17.3 ft
Casing radius:	0.0990 ft
Borehole radius:	0.5469 ft
Screen length:	10 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	0.41 ft/d
y_0 =	29.57 ft

E-4. Plot for Injection Test, R-31, Screen 4



E-5. Recovery Data for Injection Test, R-31, Screen 4

t (min)	s (ft)
0.000	9.603
0.333	9.333
0.667	8.256
1.000	6.631
1.333	5.157
1.667	3.946
2.000	3.003
2.333	2.341
2.667	1.784
3.000	1.372
3.333	1.125
3.667	0.966
4.000	0.767
4.333	0.672
4.667	0.618

t (min)	s (ft)
5.000	0.566
5.333	0.436
5.667	0.393
6.000	0.353
6.333	0.356
6.667	0.272
7.000	0.240
7.333	0.301
7.667	0.226
8.000	0.209
8.333	0.160
8.667	0.235
9.000	0.131
9.333	0.160

t (min)	s (ft)
9.667	0.140
10.000	0.183
10.333	0.191
10.667	0.125
11.000	0.171
11.333	0.099
11.667	0.062
12.000	0.148
12.333	0.108
12.667	0.065
13.000	0.125
13.333	0.047
13.667	0.111
14.000	0.099

t (min)	s (ft)
14.333	0.111
14.667	0.102
15.000	0.027
15.333	0.099
15.667	0.021
16.000	0.082
16.333	0.093
16.667	0.085
17.000	0.059
17.333	0.062
17.667	0.059
18.000	0.050
18.333	0.073
18.667	0.013

E-6. Analysis of Injection Test, R-31, Screen 4

Test Date: 28 Mar 00

Aquifer Data

Saturated thickness:	77.2 ft
Anisotropy ratio (Kz/Kr):	1

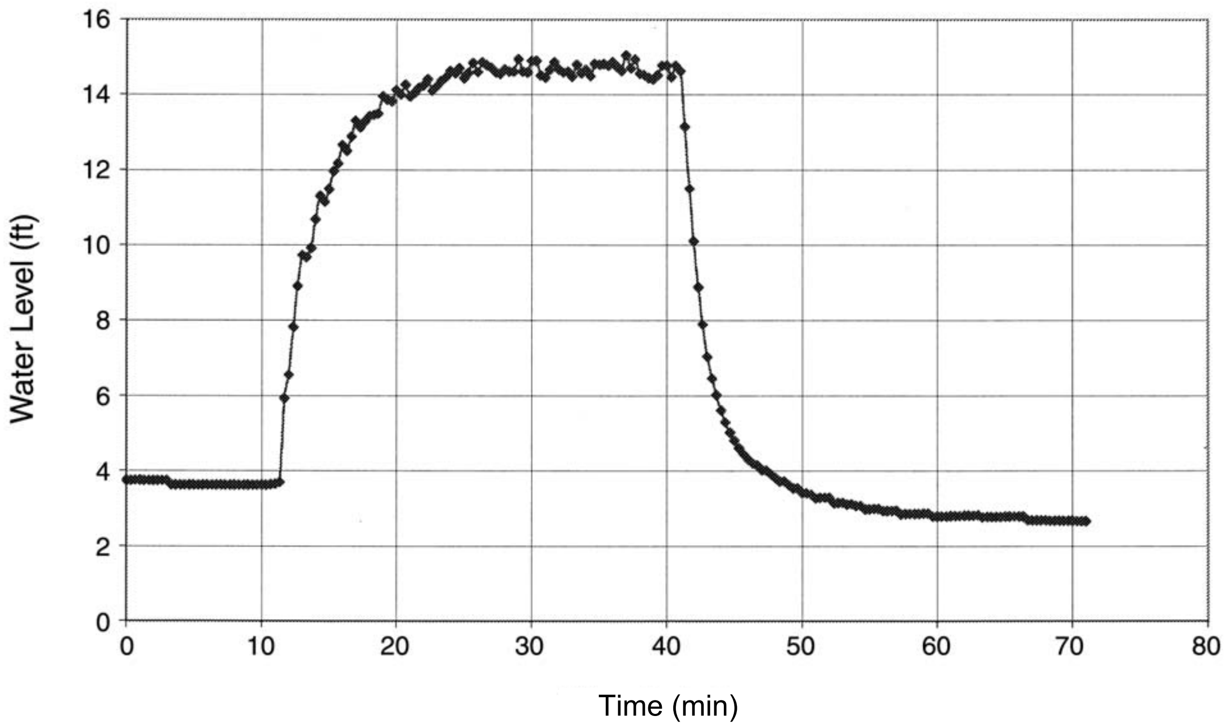
Well Data

Initial displacement:	9.6 ft
Depth of penetration:	56.6 ft
Casing radius:	0.0990 ft
Borehole radius:	0.4479 ft
Screen length:	10 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	1.23 ft/d
y_0 =	12.25 ft

E-7. Plot for Injection Test, R-31, Screen 5



E-8. Recovery Data for Injection Test, R-31, Screen 5

t (min)	s (ft)	t (min)	S (ft)	t (min)	s (ft)	t (min)	s (ft)
0.333	10.481	7.000	1.142	13.667	0.304	20.000	0.124
0.667	8.822	7.333	1.042	14.000	0.308	20.333	0.126
1.000	7.428	7.667	1.046	14.333	0.312	20.667	0.129
1.333	6.204	8.000	0.956	14.667	0.317	21.000	0.132
1.667	5.201	8.333	0.858	15.000	0.256	21.333	0.135
2.000	4.367	8.667	0.862	15.333	0.261	21.667	0.138
2.333	3.791	9.000	0.738	15.667	0.263	22.000	0.142
2.667	3.343	9.333	0.742	16.000	0.269	22.333	0.093
3.000	2.942	9.667	0.697	16.333	0.173	22.667	0.098
3.333	2.617	10.000	0.604	16.667	0.178	23.000	0.099
3.667	2.349	10.333	0.610	17.000	0.180	23.333	0.102
4.000	2.131	10.667	0.617	17.333	0.184	23.667	0.105
4.333	1.933	11.000	0.607	17.667	0.187	24.000	0.108
4.667	1.773	11.333	0.465	18.000	0.190	24.333	0.109
5.000	1.633	11.667	0.474	18.333	0.193	24.667	0.111
5.333	1.514	12.000	0.481	18.667	0.109	25.000	0.112
5.667	1.478	12.333	0.432	19.000	0.113	25.333	0.115
6.000	1.348	12.667	0.438	19.333	0.116	25.667	0.014
6.333	1.339	13.000	0.393	19.667	0.119	26.000	0.013
6.667	1.233	13.333	0.399				

E-9. Analysis of Injection Test, R-31, Screen 5

Test Date: 10 Mar 00

Aquifer Data

Saturated thickness:	198.9 ft
Anisotropy ratio (Kz/Kr):	1

Well Data

Initial displacement:	12.0 ft
Depth of penetration:	143.4 ft
Casing radius:	0.0990 ft
Borehole radius:	0.4479 ft
Screen length:	10 ft
Filter pack porosity:	0.25

Solution

Analytical method:	Bouwer-Rice
Conceptual model:	confined
K =	0.75 ft/d
y_0 =	10.94 ft

Note: *During the course of testing at R-31, it was learned that the well had not been properly developed. Thus, a second round of testing followed further development. However, in the interest of time, screen 5 was not retested. Thus, the results presented are probably less than would have been obtained had the screen been retested.*

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